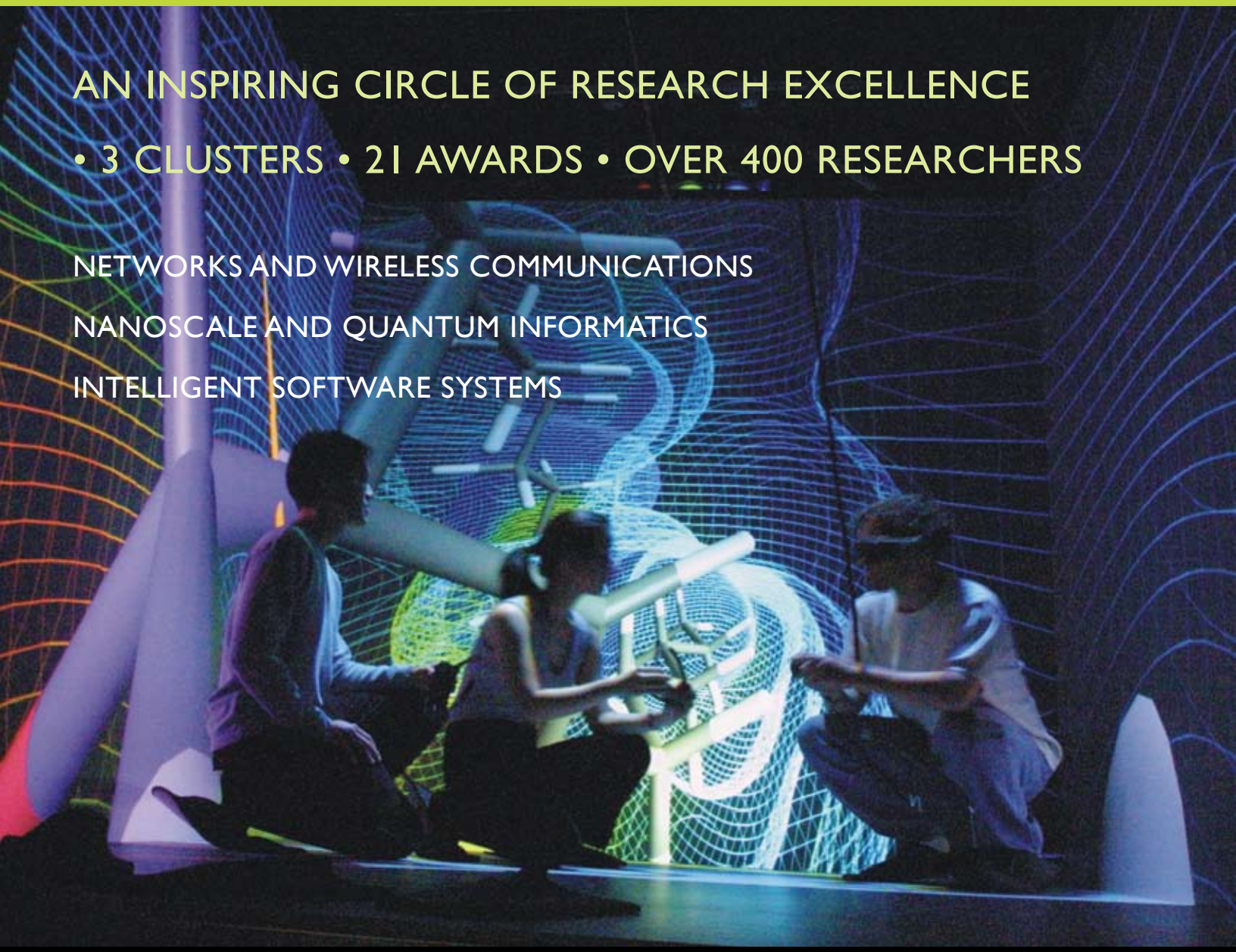
iCORE ALBERTA INFORMATICS CIRCLE OF RESEARCH EXCELLENCE

Research Report

APRIL 2004 - MARCH 2005 VOLUME 4



AN INSPIRING CIRCLE OF RESEARCH EXCELLENCE

• 3 CLUSTERS • 21 AWARDS • OVER 400 RESEARCHERS

NETWORKS AND WIRELESS COMMUNICATIONS

NANOSCALE AND QUANTUM INFORMATICS

INTELLIGENT SOFTWARE SYSTEMS

WIRELESS COMMUNICATIONS LABORATORY • HIGH-CAPACITY DIGITAL COMMUNICATIONS LABORATORY • WIRELESS LOCATION RESEARCH GROUP • BROADBAND WIRELESS NETWORKS, PROTOCOLS, APPLICATIONS, AND PERFORMANCE • WIRELESS TRAFFIC MODELLING • ADVANCED TECHNOLOGY INFORMATION PROCESSING SYSTEMS • WIRELESS SCIENCE AND TECHNOLOGY INITIATIVE • ALGORITHMIC NUMBER THEORY AND CRYPTOGRAPHY • NANOSCALE ENGINEERING PHYSICS INITIATIVE • THIN FILM ENGINEERING • NANOSCALE INFORMATION AND COMMUNICATION TECHNOLOGIES • QUANTUM INFORMATION SCIENCE • HIGH-PERFORMANCE ARTIFICIAL INTELLIGENCE • SOFTWARE ENGINEERING AND DECISION SUPPORT • REINFORCEMENT LEARNING AND ARTIFICIAL INTELLIGENCE • INTELLIGENT SENSING SYSTEMS • COLLABORATIVE VIRTUAL ENVIRONMENTS • APPLIED BIOINFORMATICS • BIOCOMPLEXITY AND INFORMATICS

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Preface

What can be accomplished by brilliant highly-motivated people encouraged to pursue the core of their intellectual passion? Almost anything. This annual compendium of iCORE researchers' incremental accomplishments is a brief glimpse of the research legacy they are creating through their immediate leadership within the five year duration of their awards, and through the future impact and mentorship of colleagues and students working in their teams.

iCORE's mandate is not just to increase the informatics research capacity of Alberta, but to raise the quality of research activity so as to be amongst the best in the world. Indeed this is being demonstrated both by external acknowledgement of iCORE researchers' accomplishments, and by growing collaborations with the best research groups on the planet.

There are of course immediate results to measure, such as the volume impact of research investment that now sustains 21 awards, including their chair leaders, and associated research team members; over 80 faculty, and 400 graduate students, postdoctoral fellows and professional research staff. All of this is a measure of our initial iCORE investment of more than $40 million to date, augmented by collaboration with other agencies and industrial partners to provide an overall investment of close to $150 million over iCORE's five year existence.

Interpreting these measurable quantities, what does iCORE really provide? We aim for the three requirements for productive researchers: 1) the freedom to pursue their scientific passion, 2) the infrastructure, including colleagues, students, and machinery to support that passion, and 3) sufficient financial support so that their primary focus remains on requirement 1!

Like the first iCORE President and CEO, I am proud to be associated with the iCORE teams, and to have played a small part in the research progress summarized herein. Those of us who have spent a lifetime in pursuit of the goals of research will recognize that this is only a snapshot of a legacy from which contributions will last forever.

Randy Goebel
President and CEO

Introduction

Randy Goebel
President and CEO

Alongside this document, which summarizes the research accomplishments of the iCORE research teams during the period from April 2004 through March 2005, it is important to note that high quality research is about risk and unpredictability. The notion of a "predictable research breakthrough" is an oxymoron in any serious researcher's vocabulary. But what is not an oxymoron is the "passionate pursuit of the unknown." Within the wide breadth of iCORE informatics research, every researcher is immersed in and consumed by a passion to know and understand things that are not yet known.

What distinguishes these people are their efforts to date to find the knowledge boundaries of their respective disciplines, and their talent and courage to step beyond those boundaries. In their terms, the iCORE mandate is to observe the whole world of informatics research, and identify those areas in which a constituency of half a percent of the world's population can make a difference.

To date, iCORE's focus for Alberta can be clustered into a small number of informatics research categories; wired and unwired communications, innovative devices and architectures, and knowledge intensive intelligent systems. In the context of this document's summary of the past year's accomplishments, I will challenge you to confirm a few high level observations about these areas of iCORE sponsored research, and hope that you all build your own picture of how this all hangs together. This is exactly what we do when iCORE researchers all gather together once a year at the iCORE Summit, and in trying it yourself, you'll get a pretty good picture of the overall enthusiasm that drives iCORE.

Communications, Wired and Unwired

Most of us within the community of informatics research have read or at least heard of Albert Einstein's caricature of how the modern telegraph system works: "The wireless telegraph is not difficult to understand. The ordinary telegraph is like a very long cat. You pull the tail in New York, and it meows in Los Angeles. The wireless is the same, only without the cat."

Communications, the largest single cluster of iCORE activities can be loosely interpreted as work on a large variety of such "cats" and "non-cats".

More technically, the repertoire of iCORE research activities in this area include investigations on fundamental devices to both capture and send information at the lowest level of electrical signals, through the information architectures required to manage the efficient and coherent transmission of those signals, all the way to methods for securing and interpreting those signals over both physical and virtual channels.

Perhaps the most impressive aspect of all this work on wired and unwired communication is the growing number of ways in which the iCORE teams align with each other. With two iCORE Summit meetings behind us, one can examine these yearly research accomplishments and easily trace several threads connecting work from the basic design of electronic circuitry all the way through to management of communication channels, to the basic number theory that provides the foundation to secure those channels, and to example applications that improve our quality of life in using them.

Innovative Devices and Architectures

Anyone who has lived through a prairie winter knows that a puddle of water behaves differently in summer and winter: most of us are not surprised that the same stuff that might fill our shoes in the summer might instead cause us to slide and fall on our backside in the winter.

We see vastly different properties depending on the context in which that puddle exists. And similarly, the iCORE research teams working on nano scale devices and quantum computing architecture work in contexts where things don't always behave as expected.

This is one way to understand the iCORE investment in the science of nano scale properties and devices. The

point is that as we observe the behaviour of smaller and smaller things, we find that there is a boundary beyond which things don't do what we expect. Much of the iCORE research teams' work on nano science, nanotechnology, and quantum computing is done in a context of molecular level activity where the use of everything from atomic scale imaging to abstract mathematical models is held together only by a combination of research ability and stubborn perseverance.

Most physicists might think it ludicrous to couple the ideas behind things like single molecule transistors with those underlying multi-bit (qubit) quantum devices. But the reason for doing so is to help non-physicists (most of us) understand iCORE's strategic investment in what seems like an inevitable marriage between so-called physical computing and modern informatics. Computer science has always anticipated and eagerly awaited the next generation of devices and architectures. The promise of quantum parallel computing devices, orders of magnitude reduction in digital device size, power consumption, and cost, must be deeply understood to be exploited in a modern information economy.

Perhaps not everyone will discern a connecting thread from quantum computing, bi-stable molecular configurations, and light transducing nano-materials, but iCORE believes that everyone will eventually benefit from the consequences of this research.

Knowledge Intensive Intelligent Systems

Most every one has heard the description of a vacuum thermos as a device which keeps cold things cold, and hot things hot, with the subsequent question of "How does it know what's cold and hot?" Similarly, and beyond a kind of ironic humor, no one would think of the common mecury thermometer as a knowledge intensive intelligent system. Still, we ask the thermos to keep our stuff hot or cold, and we ask the thermometer to tell us the temperature.

These examples of simple physical devices serve to bring forward the issue of how we can exploit informatics to build complex systems that are capable of the same thing: to be told things, and to be asked things, in order to amplify and augment our abilities as humans. That's the whole point of knowledge intensive intelligent systems (KIIS).

Indeed all of the iCORE-supported work on KIIS can be placed somewhere along a spectrum of how much an intelligent system must know, and how it can come to know what is required. To play any game, one must come to know the rules, and must develop a strategy that helps to achieve that game's goal. When the games are simple, one can design a method for "engineering" knowledge of that game in a way that a computer can understand and use. But most of the things we consider as "intelligent" don't easily succumb to this methodology. In addition to "telling" a KIIS about the game we find that we also need to tell it how to learn about the game.

We don't need to move far from the concept of "game" to see that all modern complex systems require at least two kinds of "knowing," and at least two methods of achieving that "knowing." In terms of what to know, there is both knowledge of the task, as well as the knowledge required to explain the performance on that task. When the task is simple to evaluate, such as in winning or losing a game, we may not be concerned with how winning was accomplished. But in more complicated process-oriented tasks, for example, the task of software engineering, the knowledge required to understand and explain the goal is as complicated as the goal itself. So it is that, in the development of most KIIS, the knowledge required to communicate with human users of those systems is as important as the knowledge required to do the task.

And the only real alternative to engineering the knowledge for a task is to be able to understand how to design the components so that a KIIS can learn on its own. This notion of machine learning is rapidly becoming the modern interface of informatics to other disciplines, where the enabling aspects of KIIS are to transform domain data into information. So it is that the foundation of all KIIS is how to know, and what to know, so that complex information systems can not only perform, but provide ampliative power to us humans about how to improve performance.

By working to the understand knowledge intensive intelligent systems, and develop innovative devices and architectures, and wired and wireless communications methods, iCORE researchers are finding ways to translate their passion into Alberta's future. At iCORE, we are proud to be fostering this future. We are proud to welcome iCORE's new researchers to this effort, and are proud to welcome you to our annual research compendium. Thank you for sharing our passion!

WIRELESS COMMUNICATIONS LABORATORY

Ultra-wide bandwidth systems (UWB), multiple-input multiple-output systems (MIMO), and wideband orthogonal frequency division multiplexing (W-OFDM) are “hot” new solutions being investigated in the iCORE Wireless Communications Laboratory.

NORMAN C. BEAULIEU

iCORE Chair
Electrical and Computing Engineering, University of Alberta
http://www.ece.ualberta.ca/~iwcl/

Each year the iCORE Wireless Communications Laboratory team undergoes renewal as the important areas of wireless evolve and as excellence and productivity drive the membership.

Dr Norman C. Beaulieu has held the iCORE Wireless Communications Laboratory Chair and Professorship since 2000. University of Alberta faculty members Dr Witold Krzymien, Dr Chintha Tellambura and Dr Vincent Gaudet, as well as University of Calgary faculty member Dr Abraham Fapojuwo and new recruit, iCORE Junior Chair Masoud Ardakani, form the iCORE Wireless Communications Laboratory Team.

Dr Xiaodai Dong was recruited as iCORE Junior Chair and iCORE Research Associate from September 2000 to December 2004. The iCORE Wireless Communication Laboratory thanks Dr Dong for her past participation with the team.

EXECUTIVE SUMMARY

The overall goal of the iCORE Wireless Communications Laboratory (iWCL) research program is to create new engineering science and technologies that will lead to higher capacities in broadband wireless communication systems at lower cost. Having established an internationally recognized program of scholarly research to meet this goal, the iCORE Chair is now building an intellectual property portfolio while maintaining its scholarly activities.

The research activity of Professor Krzymieñ and his graduate students is focused on broadband high throughput packet data access to the Internet for mobile and nomadic users, employing orthogonal frequency division multiplexing (OFDM) and spread spectrum signalling, and multiple-input multiple-output (MIMO) antenna techniques. The work includes physical link layer issues such as adaptive modulation and coding, space-time coding, multiple access interference cancellation and long range channel state prediction, as well as medium access control (MAC) and radio resource management questions, such as hybrid ARQ (Automatic Repeat reQuest) and packet transmission scheduling algorithms.

Dr Fair and his graduate students are investigating efficient channel coding techniques for wireless communication systems. The three main areas of work include development of efficient turbo decoding techniques, new codes for MIMO systems, and coding techniques to reduce the peak-to-average power ratio in OFDM systems.

Dr Tellambura's research interests are focused on multi-carrier techniques and wireless fading channel communications. Particular focus is on techniques for the design of high rate, high reliability wireless networks that integrate OFDM and space-time coding.

Dr Fapojuwo and his graduate students are investigating efficient protocols and algorithms for high performance wireless communication networks. The goal is to propose, develop and analyze the performance of new and efficient protocols at the data link, transport and network layers of the open system interconnection (OSI) reference model to achieve enhanced capacity and performance in future generation wireless wide area (cellular) networks (WWANs), wireless local area networks (WLANs), and mobile ad hoc networks (MANETs).

These collaborations have resulted in an unprecedented number of successful journal and conference papers. Nineteen refereed journal papers appeared in the reporting period, all in leading international journals. A further 15 refereed journal papers were accepted in the reporting period, again all in leading international journals. In addition, 38 conference papers were presented by the iCORE Chair and his research trainees in the reporting period. A further

twenty conference papers were accepted for presentation in May, June, August, and September 2005. In addition, one invited paper was presented at a major international conference in Spain.

The iWCL has also been successful in obtaining external funding: bringing $1,411,706 of other research funding to the program. Additionally, research trainees in the program have received $293,329 in external awards.

In consequence of the achievements, awards, recognition and growth of the first forty-three months, the iWCL is now well known in the international communications research community and is increasing international and national awareness of Alberta, iCORE and the University of Alberta.

RESEARCH PROGRAM OVERVIEW

To reach the wireless communications goal of higher capacity at lower cost, new engineering science must be put into action in the development of new technologies for real world systems. In order to provide higher data transmission rates to more users without sacrificing the integrity of the received information, advances must be made in the transmission system designs and components.

The primary thrust of the iWCL research is investigation into fundamental properties, limitations, and improvements in broadband wireless systems. A secondary thrust is the application of the research results to present and future systems. To that end, the team is investigating a number of scientifically important and industrially relevant topics.

RESEARCH PROJECTS

BEAULIEU: RESEARCH PROJECTS

1) Ultra-Wide Bandwidth (UWB) Communications Systems

UWB refers to new systems and technologies that are envisioned to provide short range, high data rate services to multiple users in an unlicensed transmission format. UWB systems are attracting great scientific and industrial interest. These systems are unconventional in that they spread the information signal over an extremely wide bandwidth, occupying many gigaHertz of spectrum. Correspondingly, the signals have an extremely small power spectral density and appear as noise to existing users. Further, unlike conventional wireless communication systems that are carrier-based, an UWB system is a carrier-less system, which transmits the digital information without translating it to a carrier frequency. As an emerging technology, UWB offers great potential as an area where one can make fundamental theoretical contributions and at the same time develop technology that can lead to socio-economic benefits for the supporting community. Our team has derived the only mathematical solution for predicting the bit error rate (BER) in a multiple access environment due to the multi-user interference, that is accurate for all regions of signal-to-noise ratio (SNR). Using this solution, we have undertaken the first accurate BER comparison of time-hopping (TH) UWB systems employing pulse position modulation (PPM) and binary phase shift keying (BPSK).Our team is well positioned to conduct further research on UWB receiver design, building on our past research and on the effects of quantization on signal detection. In this work, we expect to find new non-coherent receiver designs, possibly leading to intellectual property.

2) Orthogonal Frequency Division Multiplexing (OFDM) Systems

OFDM is a transmission aimed for high speed wireless data communication, and is also relevant to digital audio and video broadcasting. OFDM has undergone three generations, each generation representing major advances in technology, performance and cost over previous generations. The benefits of third generation OFDM make it popular in today's broadband wireless communications industry, and new OFDM technologies are expected to be leading candidates for fourth generation wireless (4G) systems. A shortcoming of OFDM is the intercarrier interference (ICI) that results from frequency offsets. A novel pulse-shape discovered by our team has been shown to improve the performance of typical OFDM systems. Further new insights and results about pulse-shaping recently published by our team will be applied to the OFDM pulse-shaping problem in ICI environments.

Further proposed work on equalization for OFDM will have two aspects. The first is designing better equalizers for OFDM systems using particular modulation formats. The second is designing equalizers for zero-padding DCT OFDM systems.

3) Multi-user Detection and Interference Rejection

The development of multi-user detection techniques is one of the most important recent advances in communications technology. Frequency spectrum is a limited resource and multiple users must share spectrum. Multi-user detection techniques have the potential to increase system capacity by joint processing of multiple interfering user signals. Optimal multi-user detection receivers are prohibitively complex. In consequence, much research has been

done on sub-optimal multi-user detection techniques and on the related topic of interference rejection. Most multi-user detection and interference rejection research has focused on multi-user detection for code division multiple access (CDMA) spread spectrum (SS) systems. Meanwhile, greater user capacities can be achieved in all wireless systems: frequency division multiple access (FDMA), time division multiple access (TDMA) and UWB systems, by employing multi-user detection and interference rejection techniques, and letting several users share one communication channel. Building on recent research done at the iCORE Wireless Communications Laboratory our team will investigate individually optimal and jointly optimal receiver designs for co-channel interference (CCI) environments and simplified, implementation-friendly sub-optimal versions of the optimal designs. On separate tracks, we will also investigate whitening CCI receivers and other interference rejection approaches to increasing user capacities for FDMA, TDMA, UWB and CDMA systems.

4) Multiple-Input Multiple-Output (MIMO) Systems

MIMO systems provide real-time multimedia applications at high data rate and low latency, and also provide robustness to interference and significantly improve the error rate performance. Our team will perform detailed investigations into the fundamental limits of MIMO systems and into application strategies for approaching them. Our research will include:

- Non-coherent space time systems
- Smart antennas and adaptive modulation
- Low-complexity space-time coding systems and applications to wireless sensor networks

Furthering earlier work on low-complexity space-time coding (this code design methodology and some codes designed using it are the subject of a University of Alberta patent application), the team will develop systematic methodologies for designing codes that are robust against channel variations.

An additional focus for results and techniques obtained in our research into non-coherent space-time systems and low complexity space-time coding systems will be to design coding schemes for wireless sensor networks.

5) Computer Simulation and Semi-Analytical Techniques

Computer simulation is widely used in industry and academia to predict how well new systems and components will function and to optimize system performance. Our team has contributed some widely used computer simulation tools, including the most efficient method known for generating correlated Rayleigh samples for simulating urban fading channels. Advances in simulation methods are always needed because as the technology advances, the systems and components to be simulated become more complex. Building on our past and continuing work, we will investigate rejection sampling for efficient simulation of coding schemes. Some preliminary investigations carried out at iWCL indicate that by appropriately matching the rejection regions to the code structure

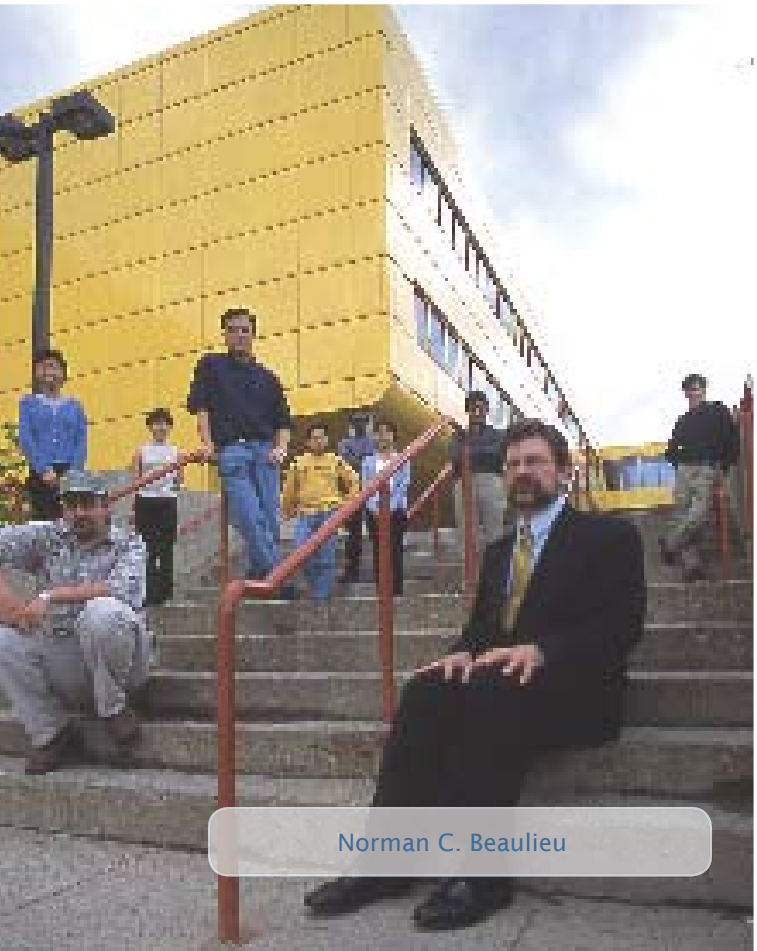
iCORE Chair Norman Beaulieu and some members of his associated research team at the 2004 Banff Informatics Summit

and to the quantization of the processed received signals, the dimensionality problem can be relieved for codes as long as hundreds and, in some cases, thousands of symbols.

We also propose to find more efficient simulation techniques for UWB systems by combining some semi-analytical models with the IEEE UWB channel model. Recent work we have published reports simple and highly accurate analytical approximations to sums of lognormal, Rayleigh and Ricean random variables. We will use these results to construct more efficient semi-analytical simulation models for UWB systems.

6) Wireless Networking

Two key research directions for future generation wireless networks are support of multimedia applications with different Quality of Service (QoS) requirements and inter-networking between heterogeneous wireless network architectures. Firstly, we will explore the use of a cross-layer design approach for QoS support in Mobile Ad-hoc Networks (MANETs), to develop and evaluate appropriate QoS provisioning mechanisms for MANETs, to investigate the QoS robustness of multimedia applications in MANET environments in the presence of hostile wireless channel and dynamic MANET topology, and to propose a cross-layer interactions framework for QoS support in MANETs and evaluate its performance. Secondly, we will focus on mechanisms for achieving efficient and effective Wireless Local Area Network (WLAN)-Cellular Inter-networking.



Norman C. Beaulieu

WLANs provide data rates much higher than those of 2G and 3G cellular networks, but operate within a local area. WLAN and cellular network technologies are mutually complementary and their integration will present an enhanced user experience and a strong market opportunity, especially in the enterprise environment. The main objectives of the proposed research on WLAN-Cellular Inter-networking are to design and evaluate protocols and mechanisms to achieve seamless inter-network roaming between 802.11WLANs and cellular networks, to propose and evaluate mechanisms for provisioning, preserving and assuring the QoS of multimedia applications in an integrated network, and to design and evaluate protocols and mechanisms to achieve low-latency handoff of multimedia calls in an integrated network.

7) Hardware Fading Channel Simulation

Our team will build an emulator to model Rayleigh, Ricean, Nakagami and lognormal fading conditions, and be suitable for MIMO and UWB design tests. Fast simulation of communications algorithms in base-band hardware is often required in order to optimize architectural parameters, and to verify functionality at low bit error rates. Channel emulators, implemented on field-programmable gate arrays (FPGAs), have recently been used to generate high-speed additive white Gaussian noise, and can be used to test novel error control decoding schemes at lower bit error rates than would be feasible in software simulation. In this project a ubiquitous channel emulator capable of emulating diverse fading channel conditions will be implemented on an FPGA device.

The channel emulator will then be expanded into a 4x4 MIMO channel emulator. Since throughput of this emulator might be limited by the size and speed of the available FPGA devices, an application-specific integrated circuit (ASIC) version of this emulator will be designed and fabricated.

OBJECTIVES FOR NEXT YEAR

The iCORE Wireless Communications Laboratory has established itself as an internationally leading wireless research centre, creating recognition and awareness of iCORE, the University of Alberta, and Alberta in the engineering science and industrial communities. Having achieved the immediate preliminary goals, the planning for the future evolution of the research program and the development of the laboratory aims at three objectives.

The first objective is to maintain or increase the present levels of scholarly research and training of highly skilled personnel to preserve the world-class

standing of the wireless research centre in Edmonton. The primary thrust of the research is investigation into fundamental properties, limitations, and improvements in broadband wireless communication systems. A secondary thrust is the application of the research results to present and future systems. This two-pronged approach is consistent with the Chair's belief that strong fundamental research is vital to the understanding and improvement of technically challenging systems, while application of the fundamental research results is an important step in creating economic benefits for the supporting community.

The second objective is the expansion of the team by the recruitment of two Junior Chairs. The Department of Electrical and Computer Engineering has been led by a new Department Head since July 1, 2004. We are working closely with the new Department Head to build Wireless as a key strategic area in research and teaching for the department. Moreover, the success and achievements of the first 56 months of operation of the iCORE Research Chair in Wireless Communications justify consideration of expansion of the group. Proposals for the establishment of two junior chairs are in preparation. These two positions would be adjunct to the iCORE Chair. The strategy is to seek industrial partners who would co-sponsor the junior chairs with a funding agency such as iCORE or with the university. In particular, it is desirable to add strength in the areas of space-time coding and of signal processing for wireless communications.

The third objective is the development of an intellectual property portfolio on the basic premise of creating benefit for the University of Alberta, and the province of Alberta. While maintaining or increasing the stature of the group as an international centre of excellence in wireless through research, publication and the training of highly skilled personnel, all research results will be carefully reviewed with a view to potential value in intellectual property. This process will be selective and will involve consultation with industrial collaborators. Results which are assessed as having true potential for wealth creation will be submitted to TEC Edmonton Ltd. (the Technology, Entrepreneur & Company Development agency of The University of Alberta) for patent prosecution and commercialization. All inventions will be assigned to the University of Alberta; there will be no commercialization independent of the University. In cases where inventions arise in collaborative research with researchers based outside the University of Alberta, fair interest in intellectual property will be retained for the University of Alberta. Consistent with this new objective of building an intellectual property portfolio, the Chair has filed two patents and one Report of Invention in the reporting year.

KRYZMIEÑ: RESEARCH PROJECTS

Professor Krzymieñ's current research work is the creation of key technologies essential for the future design of advanced broadband wireless packet data systems enabling bandwidth and power efficient high bit rate access to the Internet for nomadic and mobile users of data and multimedia services. The main application target of his work is 4G cellular radio systems and networks, although the technologies expected to emerge from it will also be very applicable to the design of high throughput broadband WLANs. The main research activity corresponds to the three major, and rapidly developing areas in digital wireless communications: radio link adaptation techniques and related optimized radio resource management, MIMO antenna systems and related space-time processing and coding, and effective and robust multi-carrier transmission techniques.

The team's work is currently focused on broadband high throughput packet data access to the Internet for mobile and nomadic users, employing OFDM and spread spectrum signalling, and MIMO antenna techniques. The work includes physical link layer issues such as adaptive modulation and coding, space-time coding, multiple access interference cancellation and long range channel state prediction, as well as MAC and radio resource management questions, such as hybrid ARQ and packet transmission scheduling algorithms

FAIR: RESEARCH PROJECTS

Dr Fair and his graduate students are investigating efficient channel coding techniques for digital communication systems. During the past year, this research has resulted in two journal letter items and eleven conference papers. The goal of Dr Fair's research is to develop efficient, easily implemented coding algorithms that result in improved performance in digital communication systems.

Research projects with which Dr Fair is involved include the development of:

- Efficient turbo decoding techniques
- Error control codes for MIMO wireless systems
- Techniques to limit the peak-to-average power ratio in OFDM systems
- Techniques which integrate error control codes with codes for other system constraints such as limited PAPR and specific spectral characteristics

TELLAMBURA: RESEARCH PROJECTS

Dr Tellambura's research interests are focused on multicarrier techniques and wireless fading channel communications.

The research challenge is to design economical, efficient and high-data-rate wireless systems, overcoming fading and other inherent wireless distortions in standardization of 4G or "beyond third generation" (B3G) systems. The primary goals and objectives of the research program are therefore to develop and analyze physical layer protocols for emerging wireless standards and applications. Research projects include:

- Space-time coded multi-carrier modulation for high-data-rate wireless systems
- Efficient detection of differential space-time modulation
- Efficient space-time detection
- Estimation techniques for OFDM to develop efficient detection algorithms for space-time coded multiple antenna systems
- To develop efficient algorithms for parameter estimation for multiple antenna OFDM systems

FAPOJUWO: RESEARCH PROJECTS

Dr Fapojuwo and his graduate students are investigating efficient protocols and algorithms for high performance wireless communication networks. During the past year, this research has resulted in six journal papers, and seventeen conference papers. The research has also resulted in the successful completion of four MSc theses and one MEng project.

The goal of Dr Fapojuwo's research is to propose, develop and analyze the performance of new and efficient protocols at the data link, transport and network layers of the open system interconnection (OSI) reference model to achieve enhanced capacity and performance in future generation wireless WWANs, wireless local area networks, wireless personal area networks, MANETs and wireless sensor networks.

Research projects with which Dr Fapojuwo is involved during 2004 include:

- Radio resource management schemes for wireless Internet protocol (IP) networks
- Adaptive QoS techniques for CDMA2000 wireless networks
- QoS support in IEEE802.11 wireless local area networks
- Traffic measurements, modeling and characterization in wireless networks
- Impact of hidden nodes on wireless local area network performance;
- Security mechanisms in wireless local area networks
- QoS routing protocol for mobile ad hoc networks;
- Analysis of secure routing protocols for MANETs
- Medium access protocol for UWB WPAN Systems
- Interference Cancellation techniques in OFDM-WPAN Systems
- Sub-carrier Management in OFDM-based Cellular Systems
- Service discovery protocols for MANETs
- Hidden Markov Model based Speech Activation System for Wireless Home Networks
- Application of software agents to resource management in wireless networks

Objectives for the next year (2005) include:

- Design and deployment of CFI-funded wireless network testbed for testing and evaluation of the proposed protocols
- Propose and evaluate QoS routing protocols for Wireless Sensor Networks
- Design of a wireless data center
- Explore the gains and costs of cross-layer interaction as applied to wireless networks performance
- Study the implications of inter-working and inter-operability between WWAN, WLAN and MANET networks in an integrated/hybrid wireless network architecture
- Propose networking and capacity solutions for tactical MANETs

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

Team Leader

PROFESSOR NORMAN C. BEAULIEU
iCORE Chair in Broadband Wireless Communications
Canada Research Chair in Broadband Wireless Communications
Médaille K.Y. Lo Medal (2004)
Fellow of the Royal Society of Canada
NSERC E.W.R. Steacie Memorial Fellow
Fellow of the Institute of Electrical and Electronics Engineers (IEEE)
Fellow of the Engineering Institute of Canada (EIC)
Editor-in-Chief of the IEEE Transactions on Communications (2000-2003)
President of the Canadian Society for Information Theory

Beaulieu: Faculty Team Members

	ROLE	
Dr Witold A. Krzymieñ, Professor	Faculty Team Member	Rohit Sharma Professorship in Communications and Signal Processing (2003) Fellow of the Engineering Institute of Canada (EIC)
Dr Ivan Fair, Associate Professor	Faculty Team Member	
Dr Chintha Tellambura, Associate Professor	Faculty Team Member	
Dr Xiaodai Dong, Associate Professor	Faculty Team Member	
Dr Abraham Fapojuwo, Assistant Professor	Faculty Team Member	

Beaulieu: Postdoctoral Fellows

	TOPIC	AWARDS
Dr Julian Cheng	Advanced Wireless Technologies for 3G and 4G	
Dr M. Oussama Damen	Space-Time Coding and MIMO Systems	Nortel Networks Associate Research Chair in Communications
Dr Zheng Du	OFDM and Space-Time Coding	

Beaulieu: PhD Students

	TOPIC	AWARDS
Kareem Baddour	Autoregressive Simulation Methods for MIMO systems	
Yunfei Chen	Wireless Channel State and Model Parameter Estimation	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Ethan Davis	Signal Classification and Modulation Identification	
Payam Dehghani Rahimzadeh	Synchronization for OFDM Wireless Systems	
Golnaz Farhadi	Space Time Processing in MANETs	iCORE International Graduate Student Award (2004-2005) Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Sasan Haghani	Capacity of Fading Wireless Channels	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship J. Gordin Kaplan Graduate Student Award
Bo Hu	Performance Analysis and Design of UWBs	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Pavel Loskot	Efficient Semi-Analytical and Simulation Methods for Wireless System Performance Assessment	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship Mary Louise Imrie Graduate Student Award
Reza Nikjah	Novel MC-FH-CDMA Technology for Multimedia Wireless Systems	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Somasundaram Niranjayan	Modeling and analysis of channel impairments in UWB Systems	
Amir Masoud Rabiei	Multiuser Detection and Power Control	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship Mary Louise Imrie Graduate Student Award
Kathiravetpillai Sivanesan	Receiver Designs for Multiuser Detection	Conference Travel Award (IEEE Military Communication Conference 2004, Monterey, CA, USA)
Peng Tan	Novel Receivers for OFDM Communications Systems	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
David Young	A Novel Increased Data Rate Multiuser Transmission Scheme	
Xiaodi Zhang	Performance analysis of H-S/MRC systems	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship

Beaulieu: MSc Students

	TOPIC	AWARDS
Robert Carruthers	An Improved Markov Model for Signal Amplitude Fading over Wireless Channels	
Jeremiah Hu	Simple Analytic Models for Equal Gain Combining Diversity Systems	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship iCORE Science to Society Conference Scholarship J Gordon Kaplan Graduate Student Awards Walter H. Johns Graduate Studies Scholarship Alberta Learning Graduate Student Scholarship NSERC PGS
Wenyu Li	Novel Diversity Combining Schemes for Space-Time Systems	
Tim Poon	Optimal Multiuser Receiver Designs for Co-Channel Interference Environments	
Faruq Rajwani	Novel Closed-Form Approximations to Lognormal Sum Distributions	iCORE Graduate Student Scholarship NSERC PGS

Beaulieu: Undergraduate Student

	TOPIC	AWARDS
Steven Soneff	Bounds on the Number of Vectors Having a Maximum Cross-Correlation Magnitude	Dean's Research Award, Faculty of Engineering, University of Alberta NSERC Summer Undergraduate Research Scholarship President's Citation, University of Alberta Transalta Memorial Scholarship Luscar Engineering Scholarship

Beaulieu: Other Team Members

	POSITION	ROLE
Lingzhi Cao	Research Engineer	Conduct preliminary research on high-risk ideas and prepare audio-visual and outreach material
Chris Jones	System Administrator	Provide computer support to Dr Beaulieu and all team members associated with the iWCL.
Adil Kodian	System Administrator	Provide computer support to Dr Beaulieu and all team members associated with the iWCL.
Sharon Walker	Administrative Assistant	Provide administrative and secretarial assistance to Dr Beaulieu and all team members associated with the iWCL.
Sandra Abello	Administrative Assistant	Provide administrative and secretarial assistance to Dr Beaulieu and all team members associated with the iWCL.

Kryzmień: Postdoctoral Fellows

	ROLE/TOPIC	AWARDS
Dr Bartosz Mielczarek	Alberta Ingenuity Fellow/ Techniques for High Throughput Wireless Packet Data Access	
Dr Erik Haas	Visiting Scientist from the German Aerospace Centre (funded by the German side)/Advanced Algorithms for OFDM Signal Detection	

Kryzmień: PhD Students

	ROLE/TOPIC	AWARDS
Robert Elliott	TRLabs PhD Student, NSERC Canada Graduate Scholar, Alberta Ingenuity Scholar/Scheduling Algorithms for High Throughput Multiple Antenna Wireless Packet Data Systems	TRLabs Fellowship NSERC Canada Graduate Scholarship Alberta Ingenuity Studentship
Kevin Jacobson	TRLabs PhD Student, NSERC Scholar/Relay Networks for 4th Generation Cellular Systems	TRLabs Fellowship NSERC PGS B Scholarship
Chunlong Bai	TRLabs PhD Student and Alberta Ingenuity Scholar (co-supervised with Dr I.J. Fair)/Hybrid ARQ Protocols Optimized for Adaptive Multi-Carrier MIMO Wireless Packet Data Systems	Alberta Ingenuity Fund Studentship TRLabs Fellowship
Jia Liu	TRLabs PhD Student/Non-Linear Transmitter Pre-Processing Algorithms for Layered MIMO Multi-User Wireless Systems	TRLabs Scholarship
Shreeram Sigdel	TRLabs PhD Student/Efficient Receiver Algorithms for MIMO Wireless Systems Employing Adaptive Multi-Carrier Transmission	TRLabs Scholarship
Geoffrey Messier	TRLabs PhD Student/Techniques for Improved CDMA Forward Link Performance (project completed, Mr Messier graduated in summer 2004)	TRLabs Scholarship
Ge Li	TRLabs PhD Student (co-supervised with Dr I.J. Fair)/Low Density Parity Check (LDPC) Codes for MIMO Wireless Systems	TRLabs Scholarship
David Mazzarese	TRLabs PhD Student and Rohit Sharma Scholar/High Throughput Downlink Cellular Packet Data Access with Multiple Antennas and Multi-User Diversity	TRLabs Scholarship
Robert Novak	TRLabs PhD Student/Adaptive Spread Spectrum OFDM High Throughput Cellular Packet Data Systems	TRLabs Scholarship
James Z. Yang	PhD Student (co-supervised with Dr C. Schlegel)	
Kay Wee Ang	Part-time PhD student; employed by the Institute for Infocomm Research, Singapore/Improved Hybrid Subtractive Interference Cancellation Schemes (project completed, Mr Ang graduated in December 2004)	

Kryzmień: MSc Students

	ROLE/TOPIC	AWARDS
Yu Fu	MSc student, (co-supervised with Dr C. Tellambura)/Intercarrier Interference Reduction in MIMO OFDM Systems	

Kryzmień: Other Team Members

	ROLE/TOPIC	AWARDS
Robert Hang	Research Associate/ Algorithms for Layered MIMO Systems	

Fair: Postdoctoral Fellows

	ROLE/TOPIC	AWARDS
Dr Yan Xin	Postdoctoral Fellow/PAPR reduction in OFDM systems	Alberta Ingenuity Associateship

Fair: PhD Students

	ROLE/TOPIC	AWARDS
Fengqin Zhai	PhD Student/Integration of error control and constrained sequence codes	
Ge Li	PhD Student (Co-supervised with Dr Krzymień)/Low density parity check (LDPC) codes for MIMO wireless systems	
Chunlong Bai	PhD Student (Co-supervised with Dr Krzymień)/Hybrid ARQ coding schemes for adaptive high throughput wireless data links employing MIMO antenna systems	Alberta Ingenuity Fund Full-time Studentship TRLabs Fellowship
Yongguang Zhu	PhD Student/Constrained sequences	
Emma Frontana	PhD Student/PAPR and ICI reduction in OFDM systems	CONACYT Scholarship

Fair: MSc Students

	ROLE/TOPIC	AWARDS
Aaron Hughes	MSc Student/Integration of error control and constrained sequence codes	TRLabs Scholarship
Ali Alavi	MSc Student (co-supervised with Dr Tellambura)/Techniques for peak-to-average power ratio reduction in OFDM systems (defended his MSc thesis in December 2004)	
Marco Castellon	MSc Student (co-supervised with Dr Elliot)/Development of power efficient turbo decoder	

Tellambura: Postdoctoral Fellows

	ROLE/TOPIC	AWARDS
Dr Wen Chen	PDF/Coding for OFDM	

Tellambura: PhD Students

	ROLE/TOPIC	AWARDS
Dung Ngoc Dao	PhD Student/Space division multiple access methods	
Saeed Fouladi Fard	PhD Student/Nonlinear decoding methods for CDMA	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Alireza Ghaderipoor	PhD Student/Space-time Coding and Decoding Techniques	Alberta Ingenuity Fund Full-time Studentship iCORE Graduate Student Scholarship
Yue Wu	PhD Student/Space-time coding techniques	
Luqing Wang	PhD Student/Reduction of High Peaks of OFDM Signals	

Tellambura: MSc Students

	ROLE/TOPIC	AWARDS
Tao Cui	MSc Student/Efficient decoding methods for high data rate systems	Alberta Ingenuity Studentship iCORE Graduate Student Scholarship
Yu Fu	MSc Student/Interference Cancellation for OFDM	
Saeed Kaviani	MSc Student/Closed-loop Transmit Diversity for Multiple Antenna Systems	
Yunxia Chen		Successfully defended her MSc thesis in August 2004
Ali Alavi		Successfully defended his MSc thesis in December 2004

Fapojuwo: Postdoctoral Fellows

	ROLE/TOPIC	AWARDS
Dr Jiang Zhu	Medium Access Protocols for WPANs and WLANs	

Fapojuwo: PhD Students

	ROLE/TOPIC	AWARDS
Abdul Hasib	PhD Student Joint Radio Resource Management in WLAN-Cellular Network	
Xiao Liu	PhD Student/SIM-based WLAN Authentication	TRLabs Scholarship NSERC Graduate Scholarship

	ROLE/TOPIC	AWARDS
Ian Lee	PhD Student/Wireless Multimedia Traffic Modeling, Characterization, Performance and Control	
Changqin Huo	PhD Student (co-supervised w/Dr Sesay)/OFDM-based Downlink Multi-cell Multi-access	
Helen Lampow-Maundy	PhD Student (part-time)/WLAN and Cellular Inter-networking	
Mohamed Shehata	PhD Student (Co-supervised with Dr Eberlein)/A Semi-formal framework for requirements engineering	

Fapojuwo: MSc Students

	ROLE/TOPIC	AWARDS
Liqi Shi	MSc Student/QoS routing in MANETs	
Thaya Kumarasamy	MSc Student/Intelligent Resource Management Protocols for DS-CDMA Wireless networks	
Mudit Seth	MSc Student/Adaptive QoS Techniques for CDMA2000 networks	iCORE Graduate Student Scholarship MSc Thesis, September 2004
Xiaohua Zeng	MSc Student / Voice Activation System for Wireless Home Networks	NSERC Industrial Scholarship TRLabs Scholarship
Rob Sizeland	MSc Student (Co-supervised with Dr Davies)/Quality of Service in IEEE802.11 wireless LANs	NSERC Industrial Scholarship TRLabs Scholarship MSc Thesis, September 2004
Travis Stevens	MSc Student /QoS in MANETs	NSERC Industrial Scholarship TRLabs Scholarship
Yagi Uhuegbulem	MSc Student (Co-supervised with Dr Sesay)/Performance analysis of IEEE802.11 WLANs with exposed nodes	TRLabs Scholarship MSc Thesis, April 2004
Rajeev Babbar	MSc Student (Co-supervised with Dr Far)/Application of software agents to resource management in wireless networks	MSc Thesis, March 2005
Kevin Luo	MSc Student/Packet Scheduling mechanisms in wireless IP networks	
Kejin Huang	MSc Student/Dynamic Software Upgrading	
Chaoji Liu	MSc Student/Service Discovery protocols for MANETs	
Hemang Shah		Graduated M Eng, March 2005

COLLABORATIONS

BEAULIEU: COLLABORATIONS

PROVINCIAL

The iCORE Wireless Communications Laboratory provided funding to the iCORE High Capacity Digital Communications (HCDC) lab to August 31, 2004. The money contributed was used to fund a graduate student co-supervised by Professor Schlegel and Professor Krzymieñ.

The Masters of Internetworking Program is an initiative under the iCORE Chair in Broadband Wireless Communications to establish a program for advanced graduate level training in the strategic area of Internetworking. Increased capacity in this field is expected to greatly enhance Alberta's ICT sector in the short, medium and long terms. This program combines networking projects and specialized courses which are jointly offered between the Departments of Electrical and Computer Engineering and Computing Science. There is a strong industrial focus to the program and Cisco and Telus are major sponsors of this program, having donated close to $1M in equipment to support its training and research activities. The first intake of 15 students started the Master's degree program in September with course and lab delivery occurring on-site in Edmonton and with a distance lecture component through SAIT in Calgary. A major equipment donation has been received through Telus to supplement the existing Cisco-supplied lab. An agreement with SAIT has been signed to cover the remote delivery components in Calgary. Efforts are underway to secure additional industrial funding of the program.

Department of Mathematical and Statistical Sciences, University of Alberta (Douglas R. Wiens): Research on fading channel amplitude distribution order statistics. This collaboration has resulted in one submitted journal paper.

INTERNATIONAL

Samsung Electronics, Korea. August 23-24, 2004, Samsung Electronics sponsored a think tank, Samsung 4G Forum 2004: Migration Paths Towards 4G Networks. This in-house event was by invitation only and the attendance of all delegates was funded by Samsung Electronics. The event brought together around 150 leaders of wireless communications from around the world. Manufacturers, service providers, industry researchers and university researchers were all well represented at this important meeting to discuss global strategy and the path towards 4G technology.

The President of Telecommunications Network Business Samsung Electronics, Ki-Tae Lee comments, "Together, we have opened a path towards 4G technology. Moreover, we have built relationships and consensus that will allow our collective vision to become reality."

Laboratory for Information and Decision Systems – Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, U.S.A. (Moe Win): Research on hybrid selectron/maximal ratio diversity combining digital receivers. This collaboration has resulted in one published journal paper and one submitted journal paper in the reporting period.

Electronics and Telecommunications Research Institute (ETRI), Daejeon, South Korea (S.J. Lee): Research on multicode DS-CDMA systems. This collaboration has resulted in one accepted journal paper and one submitted conference paper in the reporting period.

Department of Engineering Science, University of Modena, Modena, Italy (Maria Luisa Merani): Research on efficient generation of cross-correlated fading amplitude sequences for simulation of correlated branch diversity systems. This collaboration has resulted in one journal paper published in the reporting period.

Department of Electrical Engineering, University of Missouri, Columbia, Missouri, U.S.A. (Chengshan Xiao): Research on novel channel models and simulation techniques for line-of-sight fading channels and on novel diversity combining methods. This collaboration has resulted in two submitted journal papers and one published conference paper in the reporting period.

INDUSTRIAL

The iCORE Chair continued as Director of the Corporation of Eleven Engineering Incorporated, Edmonton, Alberta in the reporting period. He has been actively involved in technology and product planning as well as in the recruitment of highly qualified personnel.

TELLAMBURA: COLLABORATIONS

INSTITUTION	NATURE OF COLLABORATION
INTERNATIONAL	
A. Annamalai Electrical Engineering Department, Virginia Tech, USA	Research on diversity systems and their performance in wireless environments.
M. Parker Electrical Engineering Department, University of Bergen, Norway	Research on peak power reduction for OFDM systems

FAPOJUWO: COLLABORATIONS

INSTITUTION	NATURE OF COLLABORATION
INDUSTRIAL	
General Dynamics Canada	Networking and capacity solutions for tactical mobile ad hoc networks.
Telus Mobility	Development of a network-level simulator for CDMA200 (1xRTT) performance simulation

INTELLECTUAL PROPERTY

PATENTS	TITLE/NAME	STATUS
N. C. Beaulieu and Y.Chen	"Receiver for Pilot Symbol Assisted (Aided) Modulation"	US and Canadian Patent Application, filed October 12, 2004
N. C. Beaulieu and P. Tan	"A Novel and Improved DCT-OFDM System"	US and Canadian Patent Application, filed October 13, 2004
REPORT OF INVENTION	TITLE/NAME	STATUS
N. C. Beaulieu and P. Tan	"An Improved MMSE Equalizer for One-Dimensional Modulation OFDM Systems"	Submitted December 6, 2004

FUNDING

For this year, Norman Beaulieu and his team have attracted funding from NSERC ($334K), CFI (~$169K) and ASRA (~$185K). Other sources of funding are from the University of Alberta ($97K) and industry (~$75K). Dr Beaulieu is a Tier 1 Canada Research Chair which contributes $200K each year to his research program.

PUBLICATIONS

BEAULIEU

REFEREED JOURNAL PUBLICATIONS

N. C. Beaulieu and C. Cheng, "Efficient Nakagami-m Fading Channel Simulation," *IEEE Transactions on Vehicular Technology*, vol. 54, pp. 413-424, March 2005.

N. C. Beaulieu and Y. Chen, "Maximum Likelihood Estimation of Local Average SNR in Ricean Fading Channels," *IEEE Communications Letters*, vol. 9, pp. 219-221, March 2005.

K. Sivanesan and N. C. Beaulieu, "Outage and BER of MRC Diversity in Bandlimited Micro-Cellular Systems with CCI," *IEEE Communications Letters*, vol. 9, pp. 207-209, March 2005.

A. M. Rabiei and N. C. Beaulieu, "A Simple, Intuitive Expression for the BER of a Jointly Optimal Single Cochannel Interferer BPSK Receiver," *IEEE Communications Letters*, vol. 9, pp. 201-203, March 2005.

J. Hu and N. C. Beaulieu, "Accurate Closed-Form Approximations to Ricean Sum Distributions and Densities," *IEEE Communications Letters*, vol. 9, pp. 133-135, February 2005.

J. Hu and N. C. Beaulieu, "Accurate Simple Closed-Form Approximations to Rayleigh Sum Distributions and Densities," *IEEE Communications Letters*, vol. 9, pp. 109-111, February 2005.

X. Zhang and N. C. Beaulieu, "SER and Outage of Threshold-Based Hybrid Selection/Maximal-Ratio Combining Over Generalized Fading Channels," *IEEE Transactions on Communications*, vol. 52, pp. 2143-2153, December 2004.

N. C. Beaulieu and M.O. Damen, "Parametric Construction of Nyquist-I Pulses," *IEEE Transactions on Communications*, vol. 52, pp. 2134-2142, December 2004.

N. C. Beaulieu and F. Rajwani, "Highly Accurate Simple Closed-Form Approximations to Lognormal Sum Distributions and Densities," *IEEE Communications Letters*, vol. 8, pp 709-711, December 2004.

K. E. Baddour and N. C. Beaulieu, "Accurate Simulation of Multiple Cross-Correlated Ricean Fading Channels," *IEEE Transactions on Communications*, vol. 52, pp. 1980-1987, November 2004.

B. Hu and N. C. Beaulieu, "Accurate Evaluation of Multiple Access Performance in TH-PPM and TH-BPSK UWB Systems," *IEEE Transactions on Communications*, vol. 52, pp. 1758-1766, October 2004.

K. Sivanesan and N. C. Beaulieu, "Exact BER Analysis of Bandlimited BPSK with EGC and SC Diversity in Cochannel Interference and Nakagami Fading," *IEEE Communications Letters*, vol. 8, pp. 623-625, October 2004.

N. C. Beaulieu and M. L. Merani, "Generation of Multiple Rayleigh Fading Envelope Sequences with Specified Cross-Correlations," *European Transactions on Telecommunications*, vol. 15, pp. 471-476, September-October, 2004.

X. Zhang and N. C. Beaulieu, "SER of Threshold-Based Hybrid Selection/Maximal-Ratio Combining in Equi-correlated Nakagami Fading," *IEEE Communications Letters*, vol. 8, pp. 552-554, September 2004.

C. Tellambura, J. Cheng and N. C. Beaulieu, "Performance of Digital Linear Modulations on Weibull Fading Channels," *IEEE Transactions on Communications*, vol. 52, pp. 1265-1268, August 2004.

T. V. Poon and N. C. Beaulieu, "Error Performance Analysis of a Jointly Optimal Single Cochannel Interferer BPSK Receiver," *IEEE Transactions on Communications*, vol. 52, pp. 1051-1054, July 2004.

L. Cao and N. C. Beaulieu, "Exact Error Rate Analysis of Diversity 16-QAM with Channel Estimation Error," *IEEE Transactions on Communications*, vol. 52, pp. 1019-1029, June 2004.

S. Haghani, N. C. Beaulieu and M.Z. Win, "Penalty of Hybrid Diversity for Generalized Two-Dimensional Signaling in Rayleigh Fading," *IEEE Transactions on Communications*, vol. 52, pp. 694-697, May 2004.

C. C. Tan and N. C. Beaulieu, "Transmission Properties of Conjugate-Root Pulses," *IEEE Transactions on Communications*, vol. 52, pp. 553-558, April 2004.

Y. Chen and N. C. Beaulieu, "SER of Selection Diversity MFSK with Channel Estimation Errors," accepted for publication as a full paper in *IEEE Transactions on Wireless Communications*.

S. Haghani and N. C. Beaulieu, "Revised Analyses of Postdetection Switched Combining in Nakagami-m Fading," to appear as a full paper in *IEEE Transactions on Communications*.

P. Loskot and N. C. Beaulieu, "Sample Rejection for Efficient Simulation of Binary Coding Schemes over Quantized Additive White Gaussian Noise Channels," to appear as a full paper in *IEEE Transactions on Communications*.

B. Hu and N. C. Beaulieu, "Accurate Performance Evaluation of Time-Hopping and Direct-Sequence UWB Systems in Multi-User Interference," to appear as a full paper in *IEEE Transactions on Communications*.

Y. Chen and N. C. Beaulieu, "Estimators Using Noisy Channel Samples for Fading Distribution Parameters," accepted for publication in *IEEE Transactions on Communications*.

K. E. Baddour and N. C. Beaulieu, "Robust Doppler Spread Estimation in Nonisotropic Fading Channels," accepted for publication in *IEEE Transactions on Wireless Communications*.

L. Cao and N. C. Beaulieu, "Closed-Form BER Results for MRC Diversity with Channel Estimation Errors in Ricean Fading Channels," to appear in *IEEE Transactions on Wireless Communications*.

X. Zhang and N. C. Beaulieu, "Outage Probability of MRC with Equi-Power Cochannel Interferers in Correlated Rayleigh Fading," to appear in *IEEE Communications Letters*.

Y. Chen and N. C. Beaulieu, "NDA Estimation of SINR for QAM Signals," to appear in *IEEE Communications Letters*.

Y. Chen and N. C. Beaulieu, "CRLB's for NDA ML Estimation of UWB Channels," to appear in *IEEE Communications Letters*.

J. Cheng and N. C. Beaulieu, "Error Rate of Asynchronous DS-CDMA in Nakagami Fading," accepted for publication in *IEEE Transactions on Wireless Communications*.

Y. Chen and N. C. Beaulieu, "An Approximate Maximum Likelihood Estimator for SNR Jointly Using Pilot and Data Symbols," to appear in *IEEE Communications Letters*.

Y. Chen, N. C. Beaulieu and C. Tellambura, "Novel Nakagami-m Parameter Estimator for Noisy Channel Samples," to appear in *IEEE Communications Letters*, May 2005.

X. Zhang and N. C. Beaulieu, "SER of Threshold-Based Hybrid Selection/Maximal-Ratio Combining in Correlated Nakagami Fading," accepted pending revisions for publication in *IEEE Transactions on Communications*.

P. Loskot and N. C. Beaulieu, "The Input-Output Weight Enumerator of Binary Hamming Codes," accepted pending revisions for publication in *European Transactions on Telecommunications*.

REFEREED CONFERENCE PROCEEDINGS

P. Tan and N. C. Beaulieu, "Transmitter Nyquist Shaping for ICI Reduction in OFDM Systems with Carrier Frequency Offset," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM'05),* Victoria, Canada, Aug. 24-26, 2005.

B. Hu and N. C. Beaulieu, "Accurate BER of Time-Hopping and Direct-Sequence UWB Systems in Multi-User Interference," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM'05)*, Victoria, Canada, Aug. 24-26, 2005.

Y. Chen and N. C. Beaulieu, "Estimation of Fading Distribution Parameters in Noisy Channels," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM'05)*, Victoria, Canada, Aug. 24-26, 2005.

X. Zhang and N. C. Beaulieu, "Threshold-Based Hybrid Selection/Maximal-Ratio Combining in Equi-Correlated Nakagami Fading," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM'05)*, Victoria, Canada, Aug. 24-26, 2005.

Y. Chen and N. C. Beaulieu, "Maximum Likelihood SNR Estimators for Digital Receivers," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM'05)*, Victoria, Canada, Aug. 24-26, 2005.

Y. Chen and N. C. Beaulieu, "Performance Analysis of SNR Estimator in Digital Receivers," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM'05)*, Victoria, Canada, Aug. 24-26, 2005.

W. Li and N. C. Beaulieu, "Effects of Channel Estimation Errors on Receiver Selection Combining Schemes for Alamouti MIMO Systems, "*IEEE Vehicular Technology Conference* – Fall, Dallas, Texas, Sept. 25-28, 2005.

P. Tan and N. C. Beaulieu, "An Improved MMSE Equalizer for One-Dimensional Modulation OFDM Systems, "*IEEE Vehicular Technology Conference* – Fall, Dallas, Texas, Sept. 25-28, 2005.

K. Sivanesan and N. C. Beaulieu, "Precise Outage Analysis of Selection Diversity in Bandlimited Micro-Cellular systems with Cochannel Interference," *IEEE Vehicular Technology Conference* – Fall, Dallas, Texas, Sept. 25-28, 2005.

M.O. Damen, H. El Gamal and N. C. Beaulieu, "On the Connection Between the TAST Framework and Space-Time Codes from Division Algebra," *IEEE Canadian Workshop on Information* Theory CWIT 2005, Montréal, Québec, June 5-8, 2005.

P. Tan and N. C. Beaulieu, "Exact BER Analysis of a pi/4-DQPSK OFDM System in the Presence of Carrier Frequency Offset over Frequency Selective Fast Rayleigh Fading Channels," *IEEE International Conference on Communications ICC 2005*, Seoul, Korea, May 16-20, 2005.

B. Hu and N. C. Beaulieu, "Effects of IEEE 802.11a Narrowband Interference on A UWB Communication System," *IEEE International Conference on Communications ICC 2005*, Seoul, Korea, May 16-20, 2005.

L. Cao and N. C. Beaulieu, "A Simple Efficient Procedure for Generating Bivariate Nakagami-m Fading Samples," *IEEE International Conference on Communications ICC 2005,* Seoul, Korea, May 16-20, 2005.

L. Cao and N. C. Beaulieu, "Effects of Channel Estimation Errors on Absolute Threshold-Generalized Selection Diversity Combining," *IEEE International Conference on Communications ICC 2005*, Seoul, Korea, May 16-20, 2005.

F. Rajwani and N. C. Beaulieu, "Simplified Bit Error Rate Analysis of PAPM-UWB with MRC and EGC in Lognormal Fading Channels," *IEEE International Conference on Communications ICC 2005*, Seoul, Korea, May 16-20, 2005.

S. Haghani and N. C. Beaulieu, "Symbol Error Rate Performance of M-ary NCFSK with S+N Selection Combining in Rician Fading," *IEEE International Conference on Communications* ICC 2005, Seoul, Korea, May 16-20, 2005.

A.M. Rabiei and N. C. Beaulieu, "Multiple Symbol Differential Detection of MPSK in the Presence of Frequency Offset," *IEEE International Conference on Communications ICC 2005,* Seoul, Korea, May 16-20, 2005.

B. Hu and N. C. Beaulieu, "Effects of Multi-User Interference on the Error Rate of DS-UWB Systems," *IEEE Canadian Conference on Electrical and Computer Engineering CCECE 2005*, Saskatoon, Canada, May 1-4, 2005.

X. Zhang and N. C. Beaulieu, "Triple Hybrid Selection/ Maximal-Ratio Combining in Exponentially Correlated Rayleigh Fading," *IEEE Canadian Conference on Electrical and Computer Engineering* CCECE 2005, Saskatoon, Canada, May 1-4, 2005.

N. C. Beaulieu and L. Cao, "Robust and Accurate SER Computation for M-ary Orthogonal Signalling on a Discrete Memoryless Channel," I*EEE Canadian Conference on Electrical and Computer Engineering CCECE 2005*, Saskatoon, Canada, May 1-4, 2005.

Z. Du and N. C. Beaulieu, "A Closed-Form Result for the Average Pairwise Error Probability of t=2, r=1 Differential Cyclic Unitary Space-Time Modulation," *IEEE Wireless Communications and Networking Conference WCNC2005*, New Orleans, Louisiana, Mar. 13-17, 2005.

Z. Du and N. C. Beaulieu, "A New Two Level Differential Unitary Space-Time Modulation," *IEEE Wireless Communications and Networking Conference* WCNC2005, New Orleans, Louisiana, Mar. 13-17, 2005.

Z. Du and N. C. Beaulieu, "A New Differential Monomial Space-Time Code," *IEEE Wireless Communications and Networking Conference WCNC2005*, New Orleans, Louisiana, Mar. 13-17, 2005.

K. Sivanesan and N. C. Beaulieu, "Accurate BER Analysis of Bandlimited DS-CDMA System with EGC and SC Diversity over Nakagami Fading Channels," *IEEE Wireless Communications and Networking Conference WCNC2005*, New Orleans, Louisiana, Mar. 13-17, 2005.

S. Haghani and N. C. Beaulieu, "Postdetection Switch-and-Stay Diversity in Rician Fading," *IEEE Wireless Communications and Networking Conference WCNC2005*, New Orleans, Louisiana, Mar. 13-17, 2005.

P. Loskot and N. C. Beaulieu, "Sample Rejection for Efficient Simulation of Intersymbol Interference Channels with MLSD," *IEEE Wireless Communications and Networking Conference WCNC2005*, New Orleans, Louisiana, Mar. 13-17, 2005.

K. Sivanesan and N. C. Beaulieu, "Interference Whitening Receivers for Bandlimited DS-CDMA Systems in Nakagami Fading," *IEEE Wireless Communications and Networking Conference WCNC2005*, New Orleans, Louisiana, Mar. 13-17, 2005.

Y. Chen and N. C. Beaulieu, "Optimum Diversity Receiver Structures for Combining with Estimation Errors," *IEEE GLOBECOM,* Dallas, Texas, Nov. 29-Dec. 3, 2004.

X. Zhang and N. C. Beaulieu, "Threshold-Based Hybrid Selection/Maximal-Ratio Combining Over Generalized Fading Channels," *IEEE GLOBECOM*, Dallas, Texas, Nov. 29-Dec. 3, 2004.

Z. Du, J. Cheng and N. C. Beaulieu, "Error Rate of OFDM Signals in Frequency Selective Nakagami-m Fading Channels," *IEEE GLOBECOM*, Dallas, Texas, Nov. 29-Dec. 3, 2004.

L. Cao and N. C. Beaulieu, "Bit Error Rate Analysis of Hybrid Selection Maximal-Ratio Diversity Combining with Channel Estimation Error," *IEEE GLOBECOM*, Dallas, Texas, Nov. 29-Dec. 3, 2004.

P. Tan and N. C. Beaulieu, "Improved BER Performance in OFDM Systems with Frequency Offset by Novel Pulse-Shaping," *IEEE GLOBECOM*, Dallas, Texas, Nov. 29-Dec. 3, 2004.

K. Sivanesan and N. C. Beaulieu, "CCI Mitigation Using Interference Whitening in Bandlimited Micro-Cellular BPSK Systems," *IEEE GLOBECOM*, Dallas, Texas, Nov. 29-Dec. 3, 2004.

N. C. Beaulieu and B. Hu, "A Novel Pulse Design Algorithm for Ultra-wideband Communications," *IEEE GLOBECOM*, Dallas, Texas, Nov. 29-Dec. 3, 2004.

S. Haghani and N. C. Beaulieu, "Performance of Binary NCFSK with Dual-Branch S+N Selection Combining in Ricean and Nakagami-m Fading," *IEEE GLOBECOM*, Dallas, Texas, Nov. 29-Dec. 3, 2004.

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SPECIAL/INVITED PRESENTATIONS

N.C. Beaulieu, "Wireless Research in the iCORE Wireless Communications Laboratory," Mini-Workshop, SAMSUNG ELECTRONICS, IT Center, Suwon, Korea, August 25, 2004, Invited Talk.

N.C. Beaulieu, "Wireless Research in the iCORE Wireless Communications Laboratory," SAIT, Samsung Advanced Institute of Technology, Suwon, Korea, August 20, 2004, Invited Talk.

N.C. Beaulieu, "Wireless Research in the iCORE Wireless Communications Laboratory," NORTEL NETWORKS Tech Expo 2004, Westwinds Innovation Centre, Calgary, Alberta, June 10, 2004, Invited Talk.

N.C. Beaulieu, "Wireless Research in the iCORE Wireless Communications Laboratory," iCORE Banff Informatics Summit 2004, Banff, Alberta, June 8, 2004.

N.C. Beaulieu, "Multiple Access Interference in Time Hopping Ultra-Wideband Radio," The International Society for Optical Engineering (SPPIE) Second International Symposium on Fluctuations and Noise 2004, Noise in Communication Conference, Masapalomas, Gran Canaria, Spain, May 25-28, 2004, Invited Keynote Paper.

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HIGH-CAPACITY DIGITAL COMMUNICATIONS LABORATORY

The focus of activities at the High-Capacity Digital Communications (HCDC) Laboratory, created by iCORE Professor Schlegel under iCORE funding, is the efficient transmission of digital data through a variety of currently popular transmission channels, most notably wireless channels. The goal is to transmit digital data with the least amount of resources, in terms of energy and bandwidth, and with the maximum amount of reliability.

CHRISTIAN SCHLEGEL

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www.ualberta.ca/hcdc

The goal of the High-Capacity Digital Communications (HCDC) laboratory is to be the major center of enabling digital communications technology and science in Alberta, and one of a few elite leading centers world-wide. To this end, the HCDC laboratory maintains active research contacts with other leading centers and individuals across the globe. The faculty members of the laboratory are all recognized experts in their fields. These fields are chosen to form a cohesive overarching thrust in the area of transmission of digital information. Members are selected and recruited carefully to augment the laboratory's competence and focus diverse research methodologies around our central theme.

As of May 2004, the following are the team members of the HCDC Laboratory broken down into two groups: The core team which comprises the permanent members of the research team and the extended team, which comprises members with limited-time association such as graduate students and academic visitors. The core team consists of iCORE Chair Professor Christian Schlegel, Professor Vincent Gaudet, Professor Stephen Bates, Professor Krzysztof Iniewski, Professor Bruce Cockburn, Dr Dmitry Trukhachev, Professor Witold Kryzmien, Mr Paul Goud, Mr Robert Hang and Ms Charmaine Ramdass. The extended team consists of Professor Marat Burnashev, Professor Kamil Zigangirov, Professor Lance Perez, Professor Alex Grant, Professor Behrouz Farhang, Professor Christopher Winstead, Dr Zhenning Shi, Dr David Haley, Mr Zachary Bagley and Mr Shayne Messerly.

EXECUTIVE SUMMARY

The iCORE HCDC laboratory is focused on establishing world-class expertise in the area of digital information transmission theory and systems, with an emphasis on physical layer issues.

The technical philosophy of the HCDC laboratory is one of a global view. Systems are studied with their ultimate goal in focus. Areas and methods which promise substantial gains are identified and formulated into research projects. Technologies and methodologies are studied in how they impact the overall objective of maximizing communications system efficiency. This requires expertise from the highest levels of systems, the networking and applications layers, down to the fundamental supporting implementation technologies; essentially the transistor level.

In the past year, HCDC has been contacted by several industrial entities to provide expertise in digital signal processing, primarily in error control coding. Research contracts have been signed with Sirius Radio, L3 Communications, and Aquantia Corporation. Contacts have been made with SiWorks Inc. and PMC Sierra. Most of these contacts are interested in implementations of high-performance low-density parity check (LDPC) codes, a novel key error control coding method. The HCDC holds key knowledge in this area, having built LDPC decoders in digital application specific integrated circuits (ASICs), field programmable gate arrays (FPGAs), and analog technology. In the area of LDPC decoding, the HCDC has also been awarded the University's first NSERC Ideas to Innovation (I2I) grant.

HCDC remains the premier laboratory in the implementation of analog error control decoders, having recently completed the largest analog decoder to date, and the analog decoder holding the current world record in the lowest dissipated power per decoded bit in any technology at approximately 30pJ/bit (For more detail see "http://www.engineering.ualberta.ca/news.cfm?story=32176"). New strength has been added to this project with Professor Iniewski and two jointly supervised graduate students.

The HCDC multi-input multi-output (MIMO) testbed has been used to generate extensive channel mea-

surements which are posted on the laboratory's website (http://www.ualberta.ca/hcdc). The testbed is currently being upgraded to provide the capability to operate in packet transmission mode to test wireless packet networking solutions such as the group's random-packet CDMA (RP-CDMA) system, a novel packet transmission system invented as an answer to the low efficiency of current packet transmission standards such as IEEE 802.11/IEEE 802.16 as well as other TCP over IP wireless methods.

Finally, the group has maintained a strong research record in digital communications and transmission science, strongly supported by visiting mathematician Professor Marat Burnashev from the world-renowned Institute for Problems of Information Transmission, Moscow, Russia, as well as the group's new Alberta Ingenuity Fellow, Dr Dmitry Trukhachev, a PhD graduate from Lund University, Sweden. As outreach, Professor Schlegel served as the General Chair of the IEEE Communications Theory Workshop 2005, and as the Technical Chair of the IEEE International Symposium on Information Theory, 2005. The HCDC group also hosted the 3rd International Analog Decoding Workshop in Banff, in 2004.

RESEARCH PROGRAM OVERVIEW

Communications in the technical sense encompasses many layers. The final or bottom layer entails the implementation of signal processing algorithm into silicon platforms such as ASICs and FPGAs. Above that, on the next higher layer, is the study and design of algorithmic information and signal processing. At the top layer we find the abstract levels of computer and networks protocols, which enable efficient processing of the content carried by the lower levels. At all levels, the data or information is packaged into datagrams, finite-sized packets containing identification information that helps in the administration of these datagrams. This model describes packet-centric communications, which is arguably going to be the major mode of information exchange in future ICT networks.

The HCDC is actively involved in research and systems studies at all levels, which is critical in establishing competent research in each of the individual areas since effort-benefit tradeoffs can thus be understood on a global level. The methodology is one of top-down/bottom-up. That is, theoretical ideas and concepts are used to design algorithms and sub-systems, which are used to motivate the construction of hardware components, such as FPGA cores, ASIC prototypes, or complete testbed systems. Conversely, fundamental physics addressing feasibility and limits are used to formulate requirements at the algorithmic level to respect fundamental theoretical promises and limitations. An example of the former is the construction of the HCDC's multiple antenna testbed to study and verify theoretical results on MIMO transmission systems. An example of the latter is the application of the system-theoretic concept of density evolution analysis to the study of the effect of transistor mismatch in graph-based error control decoders.

Christian Schlegel
iCORE Professor,
Canada Research
Chair

ACHIEVEMENTS OVER PAST YEAR

The HCDC laboratory has had a very successful year, particularly in the area of error control coding, where several external research contracts have been secured, and four invention disclosures and patents have been submitted.

The following is a list of achievements over the past 12 months:

- In the area of error control coding, the group has made a significant contribution to low-density parity check (LDPC) coding. Code design and decoder architecture research has led to a number of invention disclosures and publications. We have studied LDPC codes theoretically; designing low error-floor codes, as well as practically; exploring different implementation methods. Additionally, a decoder for a novel error control coding method, LDPC convolutional coding developed by visiting Professor Zigangirov, has successfully been implemented on an FPGA platform. As a result of our activities in this area, the laboratory has secured research service contracts from two US companies to explore LDPC codes and their applications. An implementation involving novel signal processing methods for an LDPC decoder has been fabricated in an ASIC and is undergoing full testing.

- Our MIMO testbed has been used in real-time channel measurement campaigns, which are published on the group's website (www.ece.ualberta.ca/hcdc) for free downloads by researchers in the field. This testbed has been demonstrated to industry on a number of occasions. Testbeds at other academic institutions typically perform measurements with off-line equipment after data collection, severely limiting the versatility of such a testbed. The HCDC testbed is currently being upgraded to provide the capability for packet communications for future ad-hoc and wireless packet systems testing.

- In the area of multiple access interference control visiting iCORE Professor Marat Burnashev, associate member Dr Zhenning Shi, Alberta Ingenuity Fellow Dr Dmitry Trukhachev, and iCORE Professor Schlegel have made some fundamental contributions on iterative interference cancellation systems, showing that simple cancellation methods, combined with appropriate error control coding and sophisticated randomized rate and power allocation schemes can approach the physical capacity limit of a multiple access channel. These observations are extremely important, since cancellation techniques are regarded as a possible future extension of current simpler detection methods. Future activities will move the direction of verifying implementability of such systems, including prototype transmitter and receiver systems which will benefit from the laboratory's expertise in FPGA test implementation techniques.

- In the area of low-complexity VLSI implementation, HCDC faculty members Professor Vincent Gaudet and Bruce Cockburn have collaborated with iCORE Professor Schlegel to advance the state-of-the-art knowledge on the implementation of high-speed large-scale digital error control decoders. In just under six months, the team and graduate students have designed and implemented a test LDPC decoder of size 256 as a custom ASIC, whose performance measures were simulated to be about a factor of four superior to the best decoder published in the open literature. In the process of this project, a novel message communications methodology has been invented which is undergoing patenting. A novel error measurement test platform has been developed to thoroughly stress-test our ASIC decoders and generate complete performance data sets.

  HCDC Professor Stephen Bates and his graduate students have implemented in a FPGA, the world's first convolutional LDPC decoder prototype and verified its performance. Current activities are targeted at making the computational processors of these decoders as efficient as possible. Much theoretical work is targeted at designing the best possible code for a given implementation, an activity which has been noted by a number of industrial parties.

  In the area of analog signal processing and computing, the HCDC laboratory can rightfully be considered a world leader, having produced the most test chips, the largest decoder and the decoder with the lowest consumed power per decoded bit; two world record decoders. The methodology of using analog computational units has made big steps towards possible implementation in future industrial applications. Analog processing holds the promise of substantially reducing the power requirement of receivers while at the same time reducing the VLSI footprint; in other words, potentially making wireless communications less dependent on current power limitations looming over the promise to further increase transmission rates.

- Dr Christopher Winstead, former senior PhD student on this project, has recently graduated

with a thesis on analog decoding of error control codes, and the laboratory is in the process of hiring four new students to continue and expand this work, as well as taking aboard Professor Krzysztof Iniewski, an expert in analog VLSI as new member of the laboratory. A jointly supervised graduate student, Mr Nima Sadeghi, has recently been hired, and the group has worked with the iCORE group of headed by Professor Haslett in Calgary to submit a joint strategic grant application to NSERC this spring. The long-term goal will be a complete analog receiver capable of operating at extremely low power levels, suitable for wireless networking technology, such as in 21st century health monitoring systems.

- In the area of packet transmission systems, graduate student Roland Kempter has designed a robust extension to the TPC/IP protocol stack which will allow random packet loss rates in the order of 0.001 without significant reduction in goodput. This will allow the seamless application of RP-CDMA on the link level. Graduate student Sumeeth Nagaraj and Dr Trukhachev have designed various lower bounds on the maximal throughput in ad-hoc packet networks which match previously established upper bounds on the capacity of such networks. A publication of these results is in preparation for the near future.

- Work on Software Defined Radio is fairly new. Tier 3 Software Defined Radio is a radio in which all the control and demodulation operations are performed in the digital domain. Complete Tier 3 AM and short wave radios have been implemented and demonstrated. The long-term goal of this project is to demonstrate the feasibility of a digital radio that is flexible enough to accommodate different wireless protocols. This project is carried out by Professor Gaudet and graduate student Jung Ko.

OBJECTIVES FOR NEXT YEAR

Research objectives for the next year are highlighted by the following points:

- The hardware test platform will be expanded by equipping it with a novel packet receiver, which will allow the reception of joint overlapping wireless data packets. Ultimately, we plan to upgrade the testbed to allow for the implementation of novel wireless packet transmission systems designed to outperform current packet transmission methods, such as the IEEE 802.11 and IEEE 802.16 standards. A first candidate will be our RP-CDMA random packet protocol using spread-spectrum transmission technology. Application of the MIMO testbed for measurements will continue with student research teams.

- In the area of multiple access communications further research is in progress on the issue of proper power assignment to a multitude of users in a multiple access environment. Research includes theoretical studies on fundamental limits, as well as studies on the limitations of different linear and non-linear iterative cancellation-based receivers. Professor Schlegel has been invited to talk on this subject at the American Mathematical Society's sectional meeting on October 21-23, 2005, at the University of Nebraska.

- Networking research will play a role in the next phase of the HCDC as we shift some emphasis from the physical layer to include medium access layer strategies into our research. This will be done through designing joint accessing and transmission methodologies such as RP-CDMA and analyzing them for their potential. Ad hoc networking research is planned to be extended as well, with two new graduate students and a planned cooperation with the computer science department on protocol issues.

- In the area of error control coding the team will continue to expand its leadership position in the design and implementation of LDPC and turbo codes for wireless, as well as wireline, standards. The goal is the construction of high-speed decoders to cater to next generation data rates which lie in the 100s of megabits per second on wireless channels and at 10Gbits/s and upward for twisted copper cables and fiber optic systems. With Dr Bates, and through its cooperation with the VLSI laboratory, HCDC has extensive FPGA and ASIC hardware experience.

- The projects on analog signal processing and computing enter a novel ambitious phase with plans to rebuild our large analog turbo decoder with improved interfaces as well as novel analog DFT-based front-ends to make the decoder suitable for extremely low power wireless receivers using an OFDM-based transmission format. Professor Schlegel was invited to lecture on this subject in July 2005 at the Italian Summer School in Bressanone, Italy.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

As of May 2004, the following are the team members of the HCDC Laboratory:

Team Leader

Professor Christian Schlegel	iCORE Professor, Canada Research Chair
	Professor Schlegel was appointed iCORE Professor in January 2002 at the University of Alberta, where he formed the HCDC team. Scientifically he contributes to research on multiple antenna communications and multiple user communications, error control coding and applications, error control decoder implementations, and network and systems design. He is well-known for his research books "Trellis Coding'' (IEEE 1997), "Trellis and Turbo Coding'' (IEEE/Wiley, 2004), and "Coordinated Multiple User Communications" (Springer 2005), as well as for general IEEE society functions, which are: General Chair of the 2005 Communication Theory Workshop to be held in June 2005, Technical Program Chair of the International Symposium on Information Theory ISIT 05), and organizer of the 3rd Analog Decoding Workshop, in June 2004. Professor Schlegel is an Invited Guest Editor for IEEE Proceedings Magazine.

Faculty Team Members

	ROLE
Dr Vincent Gaudet, Professor	Key Member
	Professor Gaudet is a recent hire by the University of Alberta with a specialty in analog VLSI and signal processing. He works with Professor Schlegel in building the analog portion of the HCDC laboratory, and supervising Mr Winstead, and newly hired graduate student Mr Nima Sadeghi in the area of analog processing. Professor Gaudet has taken leadership in the group's recently formed task force on the implementation of LDPC codes. This program has received about $100,000 of initial support from US industry and more grants are under negotiation. Professor Gaudet was also key in acquiring the NSERC I2I grant on LDPC decoders.

iCORE Professor Christian Schlegel and some of the associated researchers at the 2004 Banff Information Summit

	ROLE
Dr Stephen Bates, Professor	Key Member
	Professor Bates was hired by the University of Alberta last year and has joined the efforts of HCDC. Dr Bates is an expert in traffic modeling for wireless networks. He also has industrial experience in the design and production of ASICs. He supports HCDC in its networks research and is a member of the LDPC task force. He has recently completed the world's first implementation of an LDPC convolutional code, a novel idea that was invented by former iCORE Visiting Professor Zigangirov.
Dr Krzysztof Iniewski, Professor	Key Member
	Professor Iniewski is a new faculty member at the University of Alberta. His expertise is in analog VLSI circuits and he has over tens years of industry experience in this area. He has agreed to join forces with the HCDC laboratory to further the analog decoder projects.
Dr Witek Kryzmieñ, Professor	Associate Member
	Professor Kryzmieñ is a senior faculty member within the Department of Electrical & Computer Engineering, and also a senior researcher closely affiliated with TRLabs. Professor Kryzmieñ's research expertise is in high throughput multi-user wireless packet data access systems employing adaptive transmission, and multiple-antenna, multi-carrier and spread-spectrum techniques. He provides strategic advice to the HCDC iCORE Professor, as well as guidance to the HCDC graduate students and research engineers. Professor Kryzmieñ is the principal investigator on an NSERC Strategic Grant entitled "Enabling Technologies for Future Wireless High Throughput Packet Data Access". The grant was awarded in October 2002 for five years, and at $200K per year it is one of the largest NSERC strategic grants in the ICT area. The grant partially funds the HCDC MIMO activity.
Dr Bruce Cockburn, Professor	Associate Member
	Professor Cockburn is a University of Alberta faculty member with expertise in ASIC development. He and his graduate student have joined forces with HCDC in the LDPC task force. The plan is to implement a state-of-the art digital LDPC decoder to verify novel HCDC intellectual property recently developed.
Dr Dmitry Trukhachev	Key Member/AIF Fellow
	Dr Trukhachev, a former student of Professor Zigangirov's, visited the HCDC last year and gave a number of lectures. Dr Trukhachev has won a 2-year Alberta Ingenuity Fellowship to join HCDC as postdoctoral research fellow.

Research Team Staff

	ROLE
Paul Goud	General Lab Director
	Mr Goud was hired by the Chair in December 2001 to head the hardware development of the laboratory. He is in charge of the evolving testbed and will also execute a supervisory role starting this fall as the hardware activities expand to include co-op students and a new VHDL design engineer. To date Mr Goud has been operating and documenting the multiple antenna testbed. He has interfaced with and directed our subcontractors providing RF designs, interfaced with the L3 Communications VHDL design team (see Partners), and with SiWorks Inc., with whom we are exploring error-control coding knowledge transfer. Mr Goud has conducted and supervised channel measurements and written four research papers on these measurement campaigns and related findings.

	ROLE
Robert Hang	VHDL Design Director
	Mr Hang was hired by the Chair in December 2002 to lead the VHDL design efforts and FPGA implementations of our test and prototype equipment. He is in charge of the design details and interfaces with the Chair and graduate students on the transfer of theoretical results to FPGA implementation. During this year Mr Hang has mainly concentrated on implementing the timing recovery algorithm required by the real-time measurement equipment. Recently, Mr Hang has also been instrumental in the design of fast LDPC code core components for FPGA implementation. He is part of the LDPC taskforce. Mr Hang is paid 50 percent by an NSERC strategic grant held joint by Professors Krzymien, Schlegel, and others. Mr Hang has recently been awarded an Alberta Ingenuity Student Fellowship and is planning on formally starting his PhD program this fall.
Charmaine Ramdass	Research Coordinator
	Ms Ramdass acts as the Research Coordinator facilitating the flow of information and administrative responsibilities of the team.

Extended Team Members

	ROLE
Marat Burnashev	NSERC Visiting Professor
	Professor Burnashev visited the HCDC laboratory for a period of five months from October 2003 to March 2004. He is a world-renowned mathematician from Moscow's famous Institute for Problems of Information Transmission. Professor Burnashev has assisted the mathematical direction of academic research projects in the area of multiple access and joint detection. Professor Burnashev will visit us again later this year as an iCORE Visiting Professor.
Kamil Zigangirov	iCORE Visiting Professor
	Professor Zigangirov from Lund University in Sweden visited us last year in the capacity of iCORE visiting professor. Professor Zigangirov is an expert in error control coding research and pioneered low-density parity-check convolutional codes (LDPCC), whose feasibility for very high-throughput applications is currently being evaluated by Professor Bates and students in cooperation with Professor Zigangirov. Professors Zigangirov and Bates continue to cooperate on LDPC convolutional codes through joint contacts at the University of Notre Dame.
Lance Perez	Academic Visitor
	Professor Perez from the University of Nebraska is an associate member of Dr Schlegel's team. He is an expert in turbo coding techniques, and co-authored *Trellis and Turbo Coding* with Dr Schlegel. He is working with HCDC on a collision-based multiple access system using frequency-shift keyed modulation useful for robust wireless networks.
Alex Grant	Academic Visitor
	Professor Grant from the University of South Australia is active in the theory and practice of multiple user communications and is working with Dr Schlegel on a joint book project *Coordinated Multiple User Communications* to be published by Springer Publishing later this year, as well as on a tutorial on the subject. He orchestrated the exchange of David Haley, which targeted the implementation of an LDPC analog decoder, using the analog serial interface developed by Christopher Winstead.

	ROLE/TOPIC
Behrouz Farhang	Joint Project
	Professor Farhang at the University of Utah is working with the HCDC on the study of efficient channel estimation procedures to be incorporated into the efficient transmission systems researched for MIMO channels. Dr Farhang and Dr Schlegel currently co-supervise one graduate student and a postdoctoral research fellow at the University of Utah. Dr Farhang has a number of joint publications with HCDC members.
Christopher Winstead	Joint Project
	Professor Winstead, a former PhD student and professor at Utah State University is a noted expert on analog processing of digital data. He works with the HCDC on issues of analog decoder implementations. Professor Winstead has designed and fabricated the world's first CMOS analog error control decoder, and now the world's largest analog decoder.
Zhenning Shi	Joint Project
	Dr Shi is a Research Associate at the University of Utah, now transferring to Australia National University (ANU) as a Research Associate. He worked on joint detection for linear multiple access channels such as CDMA and MIMO channels. Dr Shi co-authored several papers with Dr Schlegel and Dr Burnashev on iterative joint detection of CDMA and MIMO capacity. Cooperation with Dr Shi is expected to continue after his transfer.
David Haley	Joint Project/Academic Visitor
	Dr Haley visited the HCDC last year for a period of three months to work with our analog design team on transferring know-how and to duplicate some of HCDC's analog designs in the implementation of an analog LDPC decoder. Unfortunately, Dr Haley's application to Alberta Ingenuity for postdoctoral support has been unsuccessful. Further cooperation is being discussed.
Zachary Bagley	Partner
	Mr Bagley is a principal engineer at L3 Communications and a VHDL/FPGA designer. He was involved in multiple antenna research conducted jointly with Dr Schlegel and Dr Farhang. He also acts as a liaison to L3 Communications, and assisted in HCDC's first US company grant this year.
Shayne Messerly	Joint Project
	Mr Messerly is a former MSc graduate from the University of Utah and currently works for L3 communications. He is supervised by Dr Schlegel and Mr Bagley. Mr Messerly is an experienced VHDL design engineer, and has just completed the VHDL design of an iterative Gauss-Seidel filter for implementation of layering filters for our research in MIMO and CDMA systems.

Research Assistants

	ROLE/TOPIC
Christian Giasson	HCDC Laboratory; LDPC Codes
Soraya Kasnavi	HCDC Laboratory; LDPC Codes
Dave Nguyen	HCDC Laboratory; Low Voltage Analog Decoding

PhD Graduate Students

	ROLE/TOPIC
Amirhossein Alimohammad	HCDC Laboratory; VLSI
Zachary Bagley	HCDC Laboratory Multiple Antenna Communications Systems
Sheryl Howard	HCDC Laboratory Low SNR Iterative Phase Estimation
Roland Kempter	University of Utah Joint Detection Packet Communications
Lukasz Krzymien	HCDC Laboratory Multiple Antenna Communications Systems
Boon Lim	HCDC Laboratory Multiple Antenna Communications Systems
Sumeeth Nagaraj	HCDC Laboratory Advanced Packet Networks
Siavash Sheikh Zeinoddin	HCDC Laboratory LDPC Codes

MSc Graduate Students

	ROLE/TOPIC
Pranavi Anand	HCDC Laboratory Area: 10 Gigabit Ethernet Systems Topic: Characterization of ANEXT in 10gbase-t Systems
Keith Boyle	HCDC Laboratory Analog Decoding
Wing-Yee Chan	HCDC Laboratory LDPC Codes
Soraya Kasnavi	HCDC Laboratory Content Addressable Memories
Jung Ko	HCDC Laboratory Software Radio
Sean Kozicki	MEng Graduate Student HCDC Laboratory LDPC Codes
Camille Leroux	Visiting Student, Université de Bretagne-Sud HCDC Laboratory LDPC Codes
David Li	HCDC Laboratory CMOS Imaging
Nima Sadeghi	HCDC Laboratory Analog Decoding
Anthony Rapley	HCDC Laboratory Topic: Stochastic Iterative Decoding on Factor Graphs NSERC PGS A (2002-2003, 2003-2004, $17.3K/annum) iCORE Graduate Student Scholarship (2002-2003, 2003-2004, $12K/annum); Walter H. Johns Fellowship (2002-2003, 2003-2004, $4.1K/annum)
Mimi Yiu	HCDC Laboratory Analog Decoding

Undergraduate Students

Mohammad Al-Sabani	Undergraduate Student Volunteer
Vincent Sauer	Undergraduate Student Volunteer Deans's Research Award recipient Faculty of Engineering

Co-op Students

Gary Bloc	ECE Co-op Student
Ghaith Saab	ECE Co-op Student

Guest Lecturer

Dr Lutz Lampe	NSERC Guest Lecturer (2004) Iterative Processing Systems iCORE Visiting Professorship (2005); Leading Researcher at the Institute for Problems of Information Transmission, Russian Academy of Sciences
Christian Peel	Guest Lecturer (April 20, 2004); Assistant Professor, Department of Electrical and Computer Engineering, University of British Columbia Seminar Topic: Sphere Decoding for Non-coherent Channels

COLLABORATIONS

The HCDC maintains strong academic partnerships and liaisons to industry. Along with several shorter term collaborative relationships, the following long-term collaborators and partners are actively contributing to our program:

University of Calgary, Professor Haslett's iCORE Group

Over the past year Professors Haslett and Schlegel have formed an alliance on low-power receiver structures. Professor Haslett's group will concentrate on RF front-end processing and Professor Schlegel's group on aspects of analog signal processing to jointly design ultra low-power receivers for medical applications. A joint strategic grant application to NSERC was submitted this spring.

L3 Communications, Salt Lake City, Utah

This company has had a long-standing liaison with Dr Schlegel and is currently supporting hardware oriented research efforts by funding Mr Zachary Bagley and Mr Shayne Messerly. Both engineers have developed VLSI systems for the transmission and reception stages of our hardware testbed. This cooperation is expected to continue. Mr Bagley and Mr Messerly will continue with their work of implementing an iterative layering processor in FPGA to be used to separate the data streams in our MIMO systems testbed. We are currently negotiating support and cooperation on the implementation of error control codes using memory-based structures on FGPAs, pioneered by Professor Bates.

University of Utah

A cooperative link exists with the University of Utah where Dr Schlegel works with Dr Behrouz Farhang on the design of efficient and rapid equalization methods for multiple antenna systems. Two Utah PhD students and a Postdoctoral Research Fellow are jointly supervised by Professors Farhang and Schlegel.

PARTICIPANTS	NATURE OF COLLABORATION
PROVINCIAL	
HCDC Laboratory, SiWorks Inc (Calgary)	The HCDC Laboratory was awarded an NSERC I2I grant for $125K in January 2005.
HCDC Laboratory, Dr Jim Haslett (University of Calgary)	NSERC Strategic Project Grant application, jointly working on an RF interface to analog decoders
HCDC Laboratory, Dr Nelson Amaral, Department of Computer Science (University of Alberta)	Implementations of network routers
HCDC Laboratory; Dr Anup Basu, Department of Computer Science (University of Alberta)	Implementation of computational CMOS image sensors
HCDC Laboratory, IEEE	HCDC Lab member Paul Goud was re-elected as the volunteer IEEE Chapter Chair of the IEEE Northern Canada Section, Computers Communications and Solid State Circuits.
NATIONAL	
HCDC Laboratory, Dr Glenn Gulak (University of Toronto) and (McGill University) Dr Warren Gross.	NSERC SRO applicationin progress
INTERNATIONAL	
HCDC Laboratory, Dr Claude Berrou (ENST-Bretagne, France); Dr Emmanuel Boutillon (Université de Bretagne Sud, France).	Application submitted for an NSERC SRO grant Collaboration active between participants
HCDC Laboratory, Dr Dan Costello Jr and Dr Kamil Zigangirov (University of Notre Dame, USA).	HCDC associate Dr. Stephen Bates is actively collaborating on the implementation of LDPC convolutional codes (LDPC-CC Decoders for Large Memory Codes) to investigate the feasibility of LDPC Convolutional Codes in deep space applications.
HCDC Laboratory; IEEE	Professor Schlegel is currently acting as General Chair for the IEEE Communication Theory Workshop, CTW'05, as Technical Chair for the IEEE Information Theory Symposium, ISIT'05, and as Associate Editor for the IEEE Transactions on Communications.
INDUSTRIAL	
HCDC Laboratory, Dr Ayyoob Abbaszadeh, Senior Engineer, L3 Communications(USA)	HCDC Laboratory members are establishing themselves as the 'coding experts' for the LDPC coding. Negotiations are in progress for another implementation research contract this year.
HCDC Laboratory, Zachary Bagley, Principal Research Engineer, L3 Communications (USA)	HCDC has demonstrated the MIMO testbed at L3 Communications in Salt Lake City, Utah. Zachary Bagley is planning interference calculation experiments on the HCDC MIMO Testbed later this year.

INTELLECTUAL PROPERTY

PATENTS	STATUS
S. Howard, C. Schlegel, V. Gaudet, S. Bates and Robert Hang, "An LDPC Check Node Decoding Approximation"	Filed in 2005
C. Winstead, C. Schlegel, "Low-voltage implementation of analog decoding circuits"	US Provisional Patent No. 2002047, filed in 2003
V. Gaudet, B. Cockburn, C. Schlegel, S. Bates, P. Goud, R. Hang, A. Rapley and S. Howard, "Method and Apparatus for Digit-Serial Communications for Iterative Digital Processing Algorithms"	Filed in 2005
E. Boutillon, G. Gulak, V. Gaudet, and D. Gnaedig, "Procede de codage et/ou de decodage de codes correcteurs d'erreurs, dispositifs et systeme correspondants"	French Patent #2838581, filed April 16, 2002, granted October 17, 2003
S. Bates, C. Schlegel, V. Gaudet and B. Cockburn, "Memory architectures for low-density parity-check convolutional code decoders"	US provisional patent application, filed in 2004

FUNDING

Christian Schlegel received additional funding from NSERC (~$196K), CFI (~$85K), CMC ($225K), AIF ($55K) and ASRA ($64K) to support work in his research lab this year. He also has industrial funding worth ~$215K, as well as funding from the University of Alberta (~$94K in-kind). Dr Schlegel holds a Tier 2 Canada Research Chair which provides $100K per year. Using iCORE's Visiting Professor program, Dr Schlegel was able to host Dr Marat Burnashev of Russia to collaborate on research.

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

S. L. Howard, V. C. Gaudet and C. Schlegel, "Soft-Bit Decoding of Regular Low-Density Parity-Check Codes", *IEEE Trans. on Circuits and Systems II*: Express Briefs, (in press).

M.V. Burnashev, C.B. Schlegel, W.A. Krzymień, Z. Shi, "Analysis of the Dynamics of Iterative Interference Cancellation in Iterative Decoding", published in *Problems of Information Transmission*, Vol. 40, No. 4, 2004, pp. 297-317.

P. Goud Jr., R. Hang, D. Trukhachev, C. Schlegel, "A Portable MIMO Testbed and Selected Channel Measurements", accepted for publication in *EURASIP Journal on Applied Signal Processing*.

G.G. Messier, W.A. Krzymień, "Improving channel decoder performance on the CDMA forward link", accepted (April 2004) for publication in the *IEEE Transactions on Wireless Communications*.

R. Novak, W.A. Krzymień, "Efficient packet data service in a spread spectrum OFDM cellular system with 2-dimensional radio resource allocation", 4th Special Issue on Multi-Carrier Spread Spectrum of the *European Transactions on Telecommunications*, vol. 15, no. 3, May/June 2004, pp. 185-199.

L. Krzymień, C. Schlegel, "Turbo Decoding with One Bit Extrinsic Quantization", *IEEE Communications Letters* (in press).

C. Schlegel, Zhenning Shi, "Iterative Multi-User Detection and Error Control Code Decoding in Random CDMA", *IEEE Transactions on Signal Processing*, (in revision)

C. Schlegel, Zhenning Shi, Marat Burnashev, "Asymptotically Optimal Power Allocation and Code Selection for Iterative Joint Detection of Coded Random CDMA", *IEEE Transactions on Information Theory*, (in revision).

B. Farhang-Boroujeny and C. Schlegel, "Bandwidth Efficient Multicarrier Realization of Rate-One Orthogonal Space-Time Block Coded Systems", submitted to *IEEE Transactions on Communications*.

D. Gnaedig, E. Boutillon, M. Jezequel, V. Gaudet, and G. Gulak, "On Multiple Slice Turbo Codes," invited for submission to the *Annales des telecommunications*, August 2004 issue.

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S. Bates, "Low Density Parity Check Convolutional Codes", 3rd Analog Decoding Workshop, June 8-9, 2004, Banff, Alberta, Canada.

V. Gaudet, "Successes and Challenges of Analog Decoding", 3rd Analog Decoding Workshop, June 8-9, 2004, Banff, Alberta, Canada.

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S. Howard, A. Rapley, C. Schlegel, and V. Gaudet, "Two New LDPC Decoding Algorithms: Soft Bit Decoding and Sub-Min-Sum Decoding", 3rd Analog Decoding Workshop, Banff, AB, June 2004.

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WIRELESS LOCATION RESEARCH GROUP

Numerous members of the research team and collaborators received fourteen major and best research paper awards and accolades that have contributed to the recognition of the iCORE Wireless Location Research Group and the Position, Location and Navigation industry in Alberta.

GÉRARD LACHAPELLE

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The iCORE Wireless Location Research Group focuses on outdoor and indoor wireless location, high performance navigation and positioning using satellite and ground-based radio frequency (RF) techniques, integration with self-contained sensors for navigation, and the development of innovative applications.

EXECUTIVE SUMMARY

The various projects conducted during the reporting period consisted of long-term basic research projects and projects arising from the constant interface with existing and new industrial partners. Collaboration with faculty members at the University of Calgary and at other universities in Canada and abroad, in addition to strategic alliances with industry and government, significantly contributed to the progress achieved on ten major research projects. These ranged from studies on the performance of GPS indoors, to the development of novel applications such as cattle motion detection to improve cattle health management.

These research projects resulted in personnel training, publications and intellectual property transfer. Personnel training in the iCORE Chair's group consisted in the completion of six MSc and four PhD students, seven of which were directly supervised or co-supervised by the Chairholder, the hiring of several research associates and the supervision and co-supervision of 35 MSc and PhD candidates, and internship and visiting students. Fourteen papers were published and several more were accepted and/or submitted for publication in refereed journals, and some 30 were presented at conferences and published in conference proceedings. The iCORE Chair made numerous invited oral presentations in Canada and abroad. Intellectual property transfer consisted in the licensing of software and in technology transfer through external contracts and grants. New partnerships were added to the existing ones, and include one Alberta-based company and two foreign corporations. In recognition of their efforts, numerous members of the research team and collaborators received 14 major and best research paper awards and accolades that have contributed to the recognition of the iCORE Wireless Location Research Group and the Position, Location and Navigation industry in Alberta.

Thanks to the success of the Chair and his collaborators in securing external sponsors for the above research activities, $1.5M was raised in external funding over the past year. In addition, the licensing of intellectual property in the form of software generated $200K. The total amount of cash raised during the reporting period was over $2.2M.

The objectives for the upcoming 12-month period are to conduct both planned and opportunity-driven research and development. The latter is considered most important for the overall activities of the Chair to remain relevant, innovative, and to maximize economic benefits.

RESEARCH PROGRAM OVERVIEW

The specific research objectives for this reporting period were as follows:

- Study the fundamental limitations of weak indoor GPS signal acquisition and tracking methods through the development of advanced evaluation algorithms and design of field tests
- Design and test a self-contained, integrated system consisting of a high sensitivity GPS receiver and MEMS accelerometers and gyros for personal location and navigation in urban canyons

- Continue the enhancement and testing of GPS real-time kinematic positioning, including the multiple reference station technique MultiRef™ using the test network deployed in Southern Alberta by the Positioning, Location and Navigation (PLAN) Group for this purpose, and investigate the use of this technique for atmospheric studies
- Continue investigations of ground-based CDMA location techniques
- Continue research into Galileo signal acquisition and tracking technologies
- Investigate the impact of various RF interference and jamming sources on GPS signals in the civilian and military context
- Design new algorithms for advanced applications that require high performance differential GPS and integrated GPS/Inertial Navigation System (INS) methods
- Seek, create and exploit new opportunities related to wireless location, positioning, navigation and innovative applications as they arise, for example, application of GPS to intelligent transportation systems and wireless location and communication application to the Alberta agriculture industry.

These objectives were achieved partly as a result of effective collaboration with other faculty members in the Department of Geomatics Engineering and strategic alliances with outside partners and sponsors.

RESEARCH PROJECTS

The following ten major projects were the focus of the Chairholder's team during the reporting period:

1) Weak GPS Signal Analysis for Indoor Location

The research group has continued to focus on performance and modeling of degraded GPS signals indoors. New research based on raw GPS signal analysis has been advanced by the development of GNSS_SoftRx™, an all-software GPS receiver developed in the PLAN group. The software receiver provides full access to all key signal-processing stages and has thus become the key component when investigating and developing advanced GPS signal processing techniques. Its inherent flexibility allows for rapid testing of novel methods, while also giving completely controlled comparisons of performance metrics. Further high-sensitivity software receiver techniques have been developed to measure very weak indoor signals more than 40 dB below open-sky levels by using signal integration up to 10 seconds. Measurements of the fading, noise, and ranging performance of these indoor signals have been conducted to model both the channel effects and the performance of indoor GPS with various receiver processing techniques. Work is on-going to enhance these tools for comprehensive testing of more degraded signal environments and the next-generation GPS civil signals being deployed in 2005.

Evaluation of high-sensitivity GPS and AGPS receiver performance indoors has continued with hardware simulator and field tests in a number of new environments. These tests have refined the ability to stochastically replicate GPS signal characteristics indoors using a hardware simulator, thus providing more accurate and high fidelity test methods for new receivers.

This work was conducted in cooperation with Professor M. Elizabeth Cannon, Department of Geomatics Engineering, Professor Richard Klukas, Okanagan University College, and the Nokia Mobile Telephone Company, Finland.

2) Outdoor/indoor personal location and navigation using GPS integrated with self-contained MEMS sensors

The design and testing of a first generation of pedestrian navigation system prototype for use in urban canyons was completed. The system consists of a high sensitivity GPS (HSGPS) receiver, and miniature MEMS accelerometers and gyros. Several strategies to integrate the measurements from these sensors were studied as a function of the dynamics of the user trajectory and the location of the MEMS sensors on the user. The sensor data was mechanized in a pedestrian dead reckoning (PDR) mode, where the position is propagated through the detection of user steps in order to have errors proportional to the distance traveled, instead of time. The analysis of the effects of errors introduced by the primary PDR system parameters, such as heading and step length on PDR position accuracy, was studied. A method for modeling PDR position error growth versus traveled distance for several stochastic step-length and heading-drift error models was proposed. The method proposed for the integration of the sensor and HSGPS data utilizes a loosely coupled integration technique with an adaptive measurement error covariance matrix. This approach is more robust in tolerating poor position and velocity HSGPS updates that are frequently undetected after receiver autonomous integrity monitoring (RAIM) statistical testing. Optimal forward filtering results were achieved when the error covariance matrix of the HSGPS measurement updates was based on the user equivalent range error (UERE) assumed for a given urban environment and geometrical dilution of precision (DOP) parameters. In the tests conducted in downtown Calgary, the distance RMS error of the

integrated solution was below 150m more than 95 percent of the time.

Part of this work was conducted with financial support from the Auto 21 National Centre of Excellence.

3) Autonomous Landing of Aircraft on Aircraft Carriers

Continued involvement with the U.S. Navy Joint Precision Approach and Landing System (JPALS) yielded interesting results related to the use of GPS carrier phase measurements. Work included the design of a field test and signal processing techniques to measure the flexure (relative motion) of an aircraft carrier's superstructure while at sea using GPS and INS measurements. Further to this, algorithms were also developed, implemented and tested to measure the relative motion between specific parts onboard the aircraft carrier. Some of the algorithms were applied to data collected onboard the USS Harry S. Truman in February 2004. Extensive analysis is planned for data being collected in April 2005. Also in support of the JPALS project, a novel method of assessing the probability with which GPS carrier phase ambiguities can be resolved to integer values was developed and implemented. The algorithm considers time-correlated errors inherent in satellite-based positioning systems, a critical factor often overlooked in most applications.

This work was conducted in cooperation with Professor M. Elizabeth Cannon, Department of Geomatics Engineering. Financial assistance was received from the U.S. Navy through a contract with ARINC.

4) Assessment of GPS II/III and Galileo Signal Performance

The forthcoming GPS II/III and Galileo signals are designed to provide more accurate measurements than currently available with GPS I. Two signals have been specifically studied, namely Galileo L1F, the open signal to be offered by Galileo, and GPS L5 that is meant to support safety-of-life applications. The following two main characteristics of Galileo L1F were studied:

The use of a BOC(1,1) modulation instead of a traditional BPSK, as used by GPS C/A signal

This modulation improves tracking accuracy, multipath mitigation and narrow-band rejection. However, it possesses false tracking lock points that can result in biased measurements. A novel tracking algorithm, for reliably removing this bias threat without significantly degrading the tracking performance, was designed and tested. A patent was submitted to the U.S. Bureau of Patents for this new signal processing technique.

Use of a dataless (or pilot) channel in quadrature with the traditional data channel.

Tracking a signal without data can significantly improve the tracking performance since it means that a better correlation gain can be achieved through longer coherent integrations, and phase tracking does not have to be insensitive to data bit transitions (or 180° phase shift). A thorough assessment of the gain induced by the presence of a pilot channel against a simple data channel was realized, and new tracking algorithms using the combined data/pilot signals to improve the overall tracking performances were developed. This work can be applied to most of the other GPS II/III and Galileo signals that use this data/pilot signals modulation.

GPS L5 is similar to the Galileo E5a/E5b signals. L5 also provides increased multipath rejection performance and improved interference protection, due to its increased chipping rate. Part of the innovation brought by GPS L5 is its use of secondary codes, namely Neuman-Hoffman (NH) codes (also present on Galileo L1F in another form) to provide an improved symbol synchronization capability and enhanced cross-correlation isolation. However, during the acquisition phase, the presence of a Doppler ambiguity will significantly degrade the NH code autocorrelation properties. This results in an increased acquisition time, as smaller frequency steps have to be chosen. To remove this effect, two new algorithms were designed and tested. It was found that, when the signal level is above normal, a frequency removal method can greatly reduce the search time. In a weak signal case, a shortened Fast Fourier Transform (FFT) method can detect the signal without a significant increase of acquisition time.

The Galileo part of the project was conducted in collaboration with the École Nationale de l'Aviation Civile, Toulouse, France.

5) High Precision Multiple Reference Station GPS Real-Time Kinematic Positioning and GPS Meteorology

Continuing research was conducted into the use of multiple reference station (MRS) for precise kinematic carrier phase GPS positioning. A new alternative approach, namely a tightly coupled method, which shows a better performance of high-accuracy relative positioning than the standard MRS method, was designed and tested. Numerous parts of the software MultiRef™ were enhanced by extensive testing using data collected on the Southern Alberta GPS Network under quiet to extreme ionospheric conditions. The new features include more efficient real-time operation, and a very powerful DGPS engine, that is, RTCM 2.3 and 3.0 standards. The first one is for compatibility with traditional DGPS surveys while the latter

is for compatibility with the forthcoming DGNSS standard. MRS algorithm research for post-mission (PM) applications is ongoing. This research is expected to significantly improve performance of MRS in PM mode by applying batch signal processing and smoothing techniques.

Southern Alberta GPS Network data was also used for studies of atmospheric water vapour estimation using GPS. This work was conducted in collaboration with the Meteorological Service of Canada (MSC) and the University of Alberta, as part of a three-year project funded by the Canadian Foundation for Climate and Atmospheric Sciences. Joint fieldwork was conducted in July 2004, with MSC launching weather balloons within the Southern Alberta GPS Network for validation case studies. The use of tropospheric measurements, namely surface temperature and dry and wet atmospheric pressure, to enhance GPS positioning was tested using continental United States data.

Many other research projects were conducted using MultiRef™ as a major tool. A deformation monitoring study in the Neapolitan Volcanic area of Italy showed that this MRS method not only helps to achieve high positioning accuracy, but also increases periodic surface deformation measurements and improves safety.

The above research was conducted in cooperation with Professors M. Elizabeth Cannon and Susan Skone, Department of Geomatics Engineering, the Società Generale d'Informatica, Italy, the Universita' Degli Studi di Napoli Parthenope, Italy, and the NOAA Forecast Systems Laboratory Demonstration Division, United States.

Gérard Lachapelle

6) Wireless Location using Ground Based Systems

Investigations into the use of cellular telephone networks to provide outdoor location were continued using a CDMA pilot signal in the PCS (1930-1990 MHz) spectrum. This project contributed to Defence Research and Development Canada's Tactical Outdoor Positioning System project (TOPS).

The major development effort dealt with the design and realization of a multi-channel CDMA receiver; the TOPS Technology Demonstrator (TOPSTD). While this development is based on conventional wireless handset receiver design technology and methodologies, special care was required to achieve the phase coherency necessary for the ranging application at hand. Hence ancillary investigations into phase stability of the TCXO and GPS frequency reference sources were undertaken, as well as meticulous circuit design of the receiver to ensure sufficient phase coherency and stability amongst the CDMA channels. The initial results indicate that the measurement noise and multipath are sufficiently low and the time synchronization accuracy sufficiently high for TOPSTD to deliver a ranging accuracy better than ten metres.

This research was conducted in cooperation with Professor J. Nielsen, Department of Electrical and Computer Engineering, Professor R. Klukas, Okanagan University College, and with Defence Research and Development Canada.

7) Livestock Tracking

Livestock tracking is now an important issue with major economic implications for Alberta in the post-BSE ranching industry. A number of national agricultural agencies are undertaking animal RF identification (RFID) tags and tracking studies. An important element of animal tracking is the location and tracking component, with GPS being the leading candidate for Alberta, given the large areas covered by livestock and prevailing open-sky conditions. The ultimate goal is the creation of networks that can track animals throughout their life and to identify the interaction between them in the event of disease diagnosis. Other important applications include security of livestock grazing on the range, birth detection and health management through movement detection patterns and rangeland management.

Current research has focused on the feasibility of using commercial GPS chipsets, originally intended for the Cell-phone industry, to track livestock for prolonged periods. One area of study has been the effect on positioning accuracy of running receivers in low-

power modes, with extended sleep periods. Research is also being conducted on extending the operational range of the tracking systems to attenuated environments such as barns or under tree canopies by using the emerging High Sensitivity GPS receiver technology. A primary focus of the research has been the miniaturization of equipment along with power management and data compression techniques to extend equipment operational time and identify specific animals. With miniaturization comes self-induced interference, which is also being investigated. Design and execution of pilot projects are underway to assess the capability of the technology and assist in the creation of new business opportunities.

This research was conducted for Feedlot Health Management Services, Okotoks, Alberta, which holds patents in several countries for related applications.

8) GPS Interference and Jamming

GPS receiver performances are affected by unintentional and intentional RF interference sources. These can result in loss of signal tracking and/or tracking errors, depending on the severity, of the effect, receiver signal tracking sensitivity and other signal tracking characteristics. Undetected tracking errors can result in large position errors. Partial loss of tracking also results in geometry degradation, which affects position accuracy. Previous research has concentrated on the characterization of interference and developing specific tests utilizing the Spirent GSS-6560 GPS Simulator and the GSS-4765 Interference Suite. Using techniques developed in the previous year's research, efforts have shifted to exploring how a receiver design affects its susceptibility to various interference patterns. In one series of tests, the effect of modulated and continuous wave interference on GPS signal acquisition was investigated utilizing GNSS_SoftRx™ developed in the PLAN group. The use of the software receiver has allowed researchers to conduct experiments on the relationship between coherent/non-coherent integration times in the receiver and susceptibility to interference from various sources. Further research with interference and the software receiver has been focusing on receiver characteristics such as correlator spacing, the impact of interference on tracking loops, and positioning accuracy. These tests are being used to develop and further test interference mitigation techniques utilizing the GNSS software receiver being developed by the group. In the related field of GPS spoofing, various spoofing techniques and their effect on military and civilian GPS receivers is being investigated. It is anticipated that techniques for recognizing and mitigating GPS spoofing will be developed.

The interference and spoofing research was conducted partly in cooperation with Professor M.E. Cannon, Department of Geomatics Engineering, Professor J. Wight, University of Carleton, and with the Department of National Defence as part of its involvement in specific military programs with NATO allies.

9) Use of Navigation in Intelligent Transportation Systems

This research focused on driver behaviour analysis and modeling for next generation Adaptive Cruise Control systems and Collaborative Driving Systems

Gérard Lachapelle and some members of the research team at the 2005 Banff Informatics Summit

(CDS) using GPS-based precise relative positioning. A Moving Base Station (MBS) approach DGPS technique was used for relative positioning of vehicles that are in platoon formation. With increasing tendency towards built-in vehicle-to-vehicle and vehicle-to-infrastructure communication capability on future vehicle platforms that enable information sharing, MBS techniques hold great potential in vehicle telematics and ITS applications. As a continuation of previous research in which cm-level MBS positioning accuracy was achieved under open-sky conditions, this research achieved sub-metre MBS positioning accuracy in urban environments between vehicles in a platoon formation.

Field tests were conducted with multiple vehicles to gather driver behaviour related data in platoon formation driving. Inter-vehicle distance and other vehicle data from these multi-vehicle surveys were used for driver behaviour analysis and modeling with the objective of better understanding car-following behaviour under CDS-like scenarios. In particular, driver headway choice, reaction to lead vehicle breaking and acceleration maneuvers, and reaction times were investigated. Capabilities and limitations of existing car-following models were investigated using field observations. An extended car-following model framework was also developed and model elements were calibrated as a part of this research.

Parts of this research were conducted in collaboration with Professor M. Elizabeth Cannon, Department of Geomatics Engineering, and the University of Sherbrooke, under Theme F of the Auto 21 Network Centre of Excellence.

10) Assessment of the NASA/JPL Mars Network Proposal for Positioning and Navigation on Mars

The positioning and navigation performance of a proposed satellite navigation constellation for Mars, called the Mars Network was investigated. The project consisted of three major tasks: assessment of network geometry, simulation of network observations, and development of positioning and orbit improvement algorithms The network was assessed with a detailed planet-wide evaluation of the satellite constellation geometry in terms of availability, accuracy and reliability. The network was found to provide good positioning coverage to both polar and equatorial users but was found to be lacking in mid-latitude regions. End-to-end simulation tools were developed for the simulation of Mars Network observations. The trajectories of the satellites were precisely modeled using numerical methods. Simple models based on recent Mars research were developed and implemented for the most significant error sources, including the effects on the navigation signals of the Mars ionosphere and troposphere. A positioning and orbit determination algorithm was developed based on a decentralized processing strategy that only requires network elements to exchange state vectors and covariance matrices while making observations of each other. The algorithm was tested in several scenarios using a simulated range and Doppler observations between the six Mars Network satellites and eight simulated ground users located at landing sites of current and future Mars-lander missions. The Mars Network was shown to be able to position

Gérard Lachapelle and ICT Research Advisory Committee member Wolfgang Wahlster at the 2005 Banff Informatics Summit

landers on Mars to accuracies of 10m after several hours of intermittent tracking. The ability of current and future lander missions to provide ground control for improving orbits and to improve lander positioning performance was demonstrated and the effect of inter-satellite observations was investigated.

This project was conducted in collaboration with Professor Skone, Department of Geomatics Engineering.

OBJECTIVES FOR THE NEXT YEAR

The planned objectives for the forthcoming period can be sub-divided into two groups, namely planned and opportunity-driven R&D, as described below. As mentioned before, the latter group is considered most important for the overall activities of the Chairholder's group to remain relevant, innovative and to maximize economic benefits that contribute to Alberta's development.

Planned Research and Development

- Continue several of the research projects in progress.
- Initiate the development of an integrated software GNSS receiver with inertial navigation sensors in ultra-tight mode to improve indoor location and improve GNSS performance under interference and jamming. Discussions with an external partner to leverage iCORE funding to receive external funding for this project are underway.
- Develop post-mission multiple reference station GPS kinematic techniques and applications and seek alliance with appropriate partners.
- Initiate research on the characteristics of the new GPS L2C and L5 signals using the new hardware GPS II signal simulator to be delivered to the PLAN Group in Summer 2005 and modified versions of GNSS_SoftRx™
- Continue to support the Department of National Defence's NAVWAR goals

Opportunity-Driven Research and Development

- Continue to monitor evolving location and communication technologies, especially disruptive technologies, and emerging novel applications and markets
- Conceptualize and design innovative methods, algorithms, processes and applications for niche markets
- Match the above potential thrusts with current personnel capabilities and acquire new in-house expertise and/or develop new collaborations as required
- Form strategic alliances to develop and test the above, maximize the creation of new intellectual property in the process and create new business opportunities for the Alberta high technology industry

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

The on-site and off-site research team members, including their role and research topics are listed in the tables below. Another table lists the awards received by team members.

It should be noted that since most graduate students are not Canadian, they are not eligible for NSERC scholarships. In addition, since they are studying in Geomatics Engineering, the few Canadians who receive NSERC scholarships are not eligible for iCORE supplements. Thus 90 percent of these students must be funded by the Chairholder's grants.

Many PhD and MSc students are in co-supervision. This is done for three reasons, namely (1) to enrich the learning and research experience of the students, (2) to assist the Chairholder in managing his workload, and (3) to provide inexperienced faculty members in the department with graduate student supervisions. Co-supervision is also used very effectively to develop collaboration with other academic departments on campus, nationally and abroad.

Team Members on Site

NAME	ROLE	TOPIC
G. Lachapelle	Team Leader	
M.E. Cannon, Geomatics Engineering	Faculty Team Member	Satellite-based location, positioning and navigation, interference, integrated systems
N. El-Sheimy, Geomatics Engineering	Faculty Team Member	GPS/MEMS sensor integration
S. Skone, Geomatics Engineering	Faculty Team Member	GPS meteorology
K. O'Keefe, Geomatics Engineering	Faculty Team Member	Satellite-based precise positioning and indoor location
R. Klukas, Adjunct Professor, Geomatics Engineering and Associate Professor, Okanagan University College, B.C.	Faculty Team Member	RF propagation, GPS indoor location, ground-based cellular telephone location systems
J. Nielsen, Electrical and Computer Engineering	Faculty Team Member	Design, prototyping and evaluation of CDMA equipment for wireless location

Research Associates, Post-Docs, Internship and Visiting Students

NAME	ROLE	TOPIC
M. Petovello	Senior Research Associate	Design of advanced GPS/INS integration algorithms and carrier phase GNSS positioning
C. Ma	Senior Research Associate	GNSS software receiver development and ground-based wireless location
J. Schleppe	Senior Research Associate	Wireless location/communication integration and system testing
N. Luo	Research Associate	Navigation system integration and multiple reference station GNSS kinematic positioning
L. Dong	Research Associate	GNSS software transmitter development and GNSS simulations
Z. Jiang	Research Associate	Navigation system integration and testing
C. Basnayake	Post-doc	Vehicular collaborative driving
A. Wieser	Visiting Scientist	Design and reliability of GPS/INS integration algorithms
Daniel Lemmon	Internship Student	GPS software development
C. Karunanayake	SAIT Internship Student	Navigation Laboratory and equipment maintenance
V. Blanchette	SAIT Internship Student	Navigation Laboratory and equipment maintenance
C. Mongrédien	Visiting International Student (France)	Galileo BOC signal tracking performance

PhD Candidates

NAME AND ROLE	TOPIC
M. Guojiang	Development of GNSS software receiver aiding methods
O. Julien	Development of Galileo BOC signal acquisition and tracking techniques
B. Zhen	Development of GPS L5 signal acquisition and tracking techniques

NAME AND ROLE	TOPIC
L. Garin	GNSS network-based distributed systems
S. Shanmugam	New GPS L2C signal evaluation
D. Lu (co-supervisor)	Ground-based CDMS Location Systems
M. Gang (co-supervisor	Navigation system integration
P. Alves, since May 2000	Multiple reference station GPS RTK positioning
O. Mezentsev	Integration of GPS and inertial navigation systems for personal outdoor/indoor navigation
Wa. Abdel-Hamid (co-supervisor)	MEMS-based INS/GPS for vehicular positioning and navigation
J. Collin (co-supervisor, Tampere University of Technology)	Integration of GPS and MEMS sensors for personal outdoor/indoor navigation
H. Kuusniemi, (co-supervisor, Tampere University of Technology)	Reliability of personal navigation and location systems
R. Edwards (co-supervisor, University of Carleton)	RF interference and jamming and counter-measures

MSc Candidates

NAME AND ROLE	TOPIC
R. Watson	Indoor GPS propagation channel modeling
D. Karunanayake (co-supervisor)	Assisted-GPS performance analyses
D. Dao	High performance multiple reference station GNSS RTK
P. Lian	GPS signal tracking loop performance enhancement
Z. Jiang	GPS signal interference analyses
B. Lin (co-supervisor)	GPS/communication integration
T. Hu (co-supervisor)	Indoor GPS propagation model evaluation and enhancement
N. Kim	GPS signal interference analyses
Y. Ahn (co-supervisor)	Effect of the atmosphere on multiple reference station GPS RTK positioning
K. Vance	GPS signal processing
D. Yao	Signal processing algorithm development
W. Yu	Signal processing algorithm development
J. Qiu	New GPS signal evaluation
C. Mongrédien (co-supervisor)	Galileo signal processing algorithm development
M. Wang	GPS kinematic positioning
S. Charkandeh	L2C signal acquisition and tracking algorithm development and testing

AWARDS

AWARDEE	AWARD
M.E. Cannon	Fellow, Canadian Academy of Engineering, June 04
G. Lachapelle	2004 Outstanding Leadership in Alberta Technology, Alberta Science and Technology (ASTech) Leadership Foundation, October 04
M.E. Cannon	Fellow, Royal Society of Canada, November 04
M.E. Cannon	NSERC Steacie Fellow, 2002-2004
G. Lachapelle	2004 Faculty of Engineering Departmental Research Excellence Award, June 04
G. Lachapelle	2004 Faculty of Engineering Research Excellence Award, June 04
O. Mezentsev, PhD candidate	Best Student paper award, GNSS 2004 International Conference, Long Beach, CA, September 2004
S. Syed, MSc candidate	Best Student paper award, GNSS 2004 International Conference, Long Beach, CA, September 2004
W. Abdel-Hamid, PhD candidate	Best Student paper award, GNSS 2004 International Conference, Long Beach, CA, September 2004
S. Deshpande, MSc candidate	Best Student paper award, GNSS 2004 International Conference, Long Beach, CA, September 2004
C. Basnayake, PhD candidate	Best Student paper award, GNSS 2004 International Conference, Long Beach, CA, September 2004
O. Julien, G. Lachapelle and M.E. Cannon	Best paper award, GNSS 2004 International Conference, Long Beach, CA, September 2004
V. Hoyle, S. Skone and N. Nicholson	Best paper award, GNSS 2004 International Conference, Long Beach, CA, September 2004
S. Syed and M.E. Cannon	Best paper award, GNSS 2004 International Conference, Long Beach, CA, September 2004

Awards Received Over Lifetime by Grant Holder (G. Lachapelle)

AWARD	YEAR
Honorary Professor, Universita' Degli Studi Di Napoli Parthenope, Naples, Italy	2003
Fellow, Canadian Academy of Engineering	2003
Fellow, U.S. Institute of Navigation	2003
Fellow, Royal Society of Canada	2002
Honorary Professor, University of Wuhan, China	2002
Kuznetsov Medal, Kuznetsov Applied Mechanics Research Institute, Russia	2000
APEGGA Frank Spragins Summit Award	2000
Full Member, Russian Academy of Navigation and Motion Control	1999
Honorary Professor, University of Electronic Science and Technology of China	1999
Alouette Award, Canadian Aeronautics and Space Institute	1998
Johannes Kepler Award, U.S. Institute of Navigation	1997
Fellow, International Association of Geodesy	1991
20 national and international research awards	1980 - present

COLLABORATIONS

Active collaboration in the form of joint research projects and/or funded research projects took place with a variety of individuals on the University of Calgary campus and external organizations, as listed in the table below.

INSTITUTION	NATURE OF COLLABORATION	RESEARCHER
PROVINCIAL		
Dept of Geomatics Engineering, University of Calgary	GNSS and MEMS sensors	M. E. Cannon, N. El-Sheimy and S. Skone
Dept of Electrical and Computer Engineering, Univ. of Calgary	Development of firmware for ground-based wireless location	J. Nielsen
Feedlot Health Management Services, Okotoks	Cattle movement monitoring	
BJ Services, Calgary	Pipeline engineering	
NATIONAL		
Okanagan University College	Indoor GPS	
Dept of Electronics, Carleton University	GPS interference analysis	
Dept of Electrical and Informatics Eng, University of Sherbrooke	NCE Auto 21 collaborative vehicular driving systems and integrated systems	
DND/DRDC-Ottawa	RF interference studies in GNSS and Tactical Outdoor Positioning System	
INTERNATIONAL		
École Nationale de l'Aviation Civile, France	Galileo signal acquisition and tracking techniques	
Universita' Degli Studi di Napoli Parthenope, Italy	Multiple reference station GPS RTK positioning	
Tampere University of Technology, Finland	Personal location and navigation	
U.S. Navy - NAWC	Aircraft buffeting measurements	
NOAA Forecast Systems Laboratory Demonstration Division, U.S.A.	Atmospheric effects on GPS	
Ministry of Finance, Government of Italy	Multiple reference station GPS RTK positioning	
INDUSTRIAL		
Major mobile phone manufacturing company	Wireless location of cellular telephones	
SiRF Technology Inc, U.S.A.	Assisted GPS receiver evaluation	
Spirent Communications, U.K.	Indoor location simulation enhancements	
U.S. Navy	Joint Precision Approach and Landing System	
Major vehicle manufacturing company	Integrated vehicular navigation systems	
FreeFlight Inc/FAA, U.S.A.	GPS/Loran integrated navigation systems	

INTELLECTUAL PROPERTY

Significant intellectual property was created during the reporting period and transferred to industry using two mechanisms, namely research contracts and software licenses. The latter are summarized in the table below, together with potential company spinoff. University Technologies International, the licensing arm of the University of Calgary, licensed the software to third parties. Over $500K of revenue was generated by software licenses during the reporting period. In addition to the above, some of the intellectual property developed by the grant holder was transferred to third parties (industry and Canadian and foreign government agencies through grants and contracts. The value of this activity during the reporting period was of the order of $500K. The total value of intellectual property transfer during the reporting period was therefore of the order of $1M.

NAME AND DESCRIPTION		STATUS
LICENSES		
MultiRef™	Multiple GPS reference station software for high precision positioning and navigation – software initiated in 2000 and being continuously enhanced	
SAINT™	Satellite And Inertial Navigation Technology, new algorithms for the real-time processing of combined GPS and inertial navigation system measurements. Software initiated in 2002 and still be enhanced	One license to a foreign company
HEADRT+™	GPS software for the determination of a mobile platform's attitude parameters. Second generation software initiated in 2000 and enhanced in 2003 to include integration with low-cost MEMS sensors	One license to a Canadian company and one license upgrade to a foreign company
NDL™	Navigation Development Library. Software initiated in 2001, and being continuously enhanced	One license to a foreign company
FLYKINRT+™	GPS software that uses carrier phase measurements for high accuracy navigation in real-time	
GNSS_SoftRx™	GPS and Galileo signal processing software used extensively for research in PLAN Group	On-going discussion with two organizations
GNSS Software Transmitter	First version of software initiated in 2002 and completed in 2003. Final name to be assigned	On-going discussion with one foreign company
C3NAVG2™	GPS positioning	Two licenses to a Canadian and a foreign company
PATENT APPLICATION		
New Unambiguous BOC (n,n) Signal Tracking Algorithm		Submitted to U.S. Bureau of Patents

FUNDING

Gerard Lachapelle and his team received funding (~$759K) from many areas, including naval, aeronautical and defense interests. His industrial sponsors have contributed a combined total of $272K in-cash and in-kind while NSERC has provided $189K. Dr Lachapelle holds a Tier 1 Canada Research Chair, which provides $200K a year.

PUBLICATIONS

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Alves, P, G. Lachapelle and M.E. Cannon (2005) Collocation-based Multiple Reference Station DGPS RTK Positioning. *Geomatica*, 59, 1,37-47.

Stirling, R., K. Fyfe, and G. Lachapelle (2005) Evaluation of a New Method of Heading Estimation for Pedestrian Dead Reckoning Using Shoe Mounted Sensors. *Journal of Navigation*, Royal Society of Navigation, Cambridge University Press, 58, 1, 31-45.

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Kuusniemi, H., G. Lachapelle and J. Takala (2004) Position and Velocity Reliability Testing in Degraded GPS Signal Environments. *GPS Solutions*, 8 4, 226-237.

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Jeon, C.W., G. Jee and G. Lachapelle (2004) Development of A Sequential Algorithm for GNSS-Based Multi-Sensor Vehicle Navigation System. I*nternational Journal of Control, Automation, and Systems,* 2, 2, 165-170.

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Pugliano, G., P. Alves, M.E. Cannon, and G. Lachapelle (2004) Valutazione delle prestazioni di un approccio Multi-Reference Station avanzato per il posizionamento e la navigazione. *Atti dell' Istituto Italiano di Navigazione*, 174 (March issue), 49-66.

Julien, O., M.E. Cannon, P. Alves, and G. Lachapelle (2004) Triple Frequency GPS/GALILEO For Ambiguity Resolution. *European Journal of Navigation*, 2, 2, 51-57.

Lachapelle, G., M.E. Cannon, R. Klukas, S. Singh, R. Watson, P. Boulton, A. Read and K. Jones (2004) Hardware Simulator Models and Methodologies for Indoor Performance Assessment of High Sensitivity Receivers. *Canadian Aeronautics and Space Journal,* 50, 3, 151-168.

Lachapelle, G., H. Kuusniemi, D. Dao, G. MacGougan, and M.E. Cannon (2004) HSGPS Signal Analysis and Performance Under Various Indoor Conditions. Navigation, *U.S. Institute of Navigation*, 51, 1, 29-43.

Dogan, U., P. Alves, G. Lachapelle, and S. Ergintav (2004) Testing a Multiple Reference Station GPS Network for Real-Time Carrier Phase-Based Positioning in the Marmara Region, Turkey. *Survey Review*, 37, 293 (July Issue), pp. 568-576.

Petovello, M., M.E. Cannon, and G. Lachapelle (2004) Benefits of Using a Tactical Grade INS for High Accuracy Positioning. Navigation, U.S. Institute of Navigation, 51, 1, 1-12.

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Zhang, H., M. Petovello, and M.E. Cannon (2005) Performance Comparison of Kinematic GPS Integrated with Different Tactical Level IMUs. CD-ROM Proceedings of NTM 2005, San Diego, 24-26 January, *The Institute of Navigation*, 12 pages.

Lian, P., G. Lachapelle, and C. Ma (2005) Improving the Tracking Performance of PLL in High Dynamics Applications. CD-ROM Proceedings of NTM 2005, San Diego, 24-26 January, *The Institute of Navigation,* 1042-1053.

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SEMINARS, INVITED PRESENTATIONS AND LECTURES

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Lachapelle, G. (2005) Advances in GNSS Technologies for Outdoor and Indoor Applications. Invited presentation, Electronics and Telecommunications Research Institute (ETRI), South Korea, 14 February.

Lachapelle, G. (2005) Geomatics Engineering at the University of Calgary. Invited presentation, Philadelphia University, Jordan, 18 January.

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Michaud, F., N. Gaubert, P. Lepage, B.Chaib-Draa, J. Laumonier, M.E. Cannon, G. Lachapelle, S. Crawford, H. Leung and D. Huang (2004) Collaborative Driving Systems – Hands-Off Driving for Improved Efficiency and Comfort. Poster Presentation, AUTO21 NCE Conference, Montréal, June 15-18.

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BROADBAND WIRELESS NETWORKS, PROTOCOLS, APPLICATIONS, AND PERFORMANCE

WIRELESS INTERNET TRAFFIC MODELLING

Two exciting Internet technologies are the World Wide Web and wireless networks. The Web has made the Internet available to the masses, through its TCP/IP protocol stack and the information-hiding principle of layering. Wireless technologies have revolutionalized the way people think about networks, by offering users freedom from the constraints of physical wires.

CAREY WILLIAMSON

iCORE Professor
Department of Computer Science, University of Calgary
http://www.cpsc.ucalgary.ca/~carey/

Dr Carey Williamson has been an iCORE Professor in the Department of Computer Science at the University of Calgary, specializing in Broadband Wireless Networks, Protocols, Applications, and Performance since July 1, 2001. He also holds an NSERC/iCORE/TELUS Mobility Industrial Research Chair (IRC) in Wireless Internet Traffic Modeling.

Combined, Dr Williamson leads a research team of 16 people with interests in wireless networks, Internet technologies, and network performance, with an applied focus on industrially-relevant network and protocol performance issues.

EXECUTIVE SUMMARY

This document summarizes research activities for the reporting year of April 1, 2004 to March 31, 2005. The highlights of this reporting year include:

- Leading an active research team that currently consists of 2 faculty members, 6 research staff, and 8 graduate students (4 PhD, 4 MSc)
- Collectively producing 17 research publications (6 journal, 9 conference, 2 book chapters), with 14 more papers (4 journal, 10 conference) currently submitted and under review
- Supervising 5 graduate students to successful completion of their MSc programs
- Acquiring the equipment for the CFI-funded ELISA laboratory
- Extensive service contributions at department, university, national, and international levels

RESEARCH PROGRAM OVERVIEW

This research program combines wireless technologies and the Web, to maximize the value of each. The applied research portion has a strong focus on experimental computer systems performance research, applying techniques such as empirical measurement, computer simulation, and analytical modeling to assess the performance of Internet systems.

The general goals of the research program are:

- To identify protocol performance problems in wireless Web communication systems;
- To propose and evaluate creative solutions to these performance problems; and
- To promote deployment of wireless Web infrastructure at the University of Calgary

RESEARCH PROJECTS

This section describes selected projects underway in our research group in 2004-2005. The chosen projects reflect the variety of network performance research carried out in the group, and complement the larger set of projects discussed in reports from previous years.

Wireless Media Streaming

We are continuing our research on wireless media servers and the portable networks paradigm. The portable network paradigm refers to the deployment and use of Web servers and multimedia servers in a wireless ad hoc networking environment, without requiring any pre-existing network infrastructure. Four research publications have resulted from this work to date.

The main emphasis in this past year has been on wireless media streaming and included a live field trial of a wireless media server with a French cinematography class. Eight concurrent unicast stored video streams were successfully delivered to students using laptops in the wireless ad hoc classroom network.

This project unifies many of the topics on which graduate students and research staff are currently working. The challenges include not just Web content delivery, but also request scheduling, wireless media streaming, quality of service, TCP protocol performance, caching, security, and ad hoc routing. This project also provides a natural linkage to a new faculty member, whose specialty is multimedia content delivery systems on the wired Internet. Wireless access networks change many of the assumptions on which multicast streaming systems are based.

The "Bad Apple" Phenomenon

Our experiments with video streaming applications in wireless LANs identifed an interesting observation that we call the "bad apple" phenomenon: when one user in the Wireless LAN (WLAN) has poor or intermittent wireless connectivity, this client can disrupt the media streaming quality for all other users in the WLAN. In other words, one "bad apple spoils the batch." Further research demonstrated that the phenomenon arises because of interactions that occur between protocols when using a shared wireless channel, a FIFO queue, and multiple stations with differing wireless channel quality.

In essence, this problem is a transient manifestation of Head Of Line (HOL) blocking, at the Medium Access Control (MAC) layer. All pending packets in the queue are blocked while the front packet undergoes retransmissions. The effective service rate of the queue diminishes. Since the media server continues to generate packets for the streaming clients, the queue fills and overflows, and packets from all clients are subject to loss. When the "bad apple" reconnects, the service rate of the WLAN queue returns to normal, and the backlog dissipates. The result of this phenomenon is that guaranteeing Quality of Service (QoS) for wireless video streaming is impossible. Performance in the WLAN will degenerate to that of the client with the worst wireless connectivity.

Our research is studying solutions to this fundamental problem, which pervades all IEEE 802.11 technologies, including IEEE 802.11e. We have three solutions in mind. The simplest is to disable MAC-layer retransmissions. However, this has the undesirable side effect of making the WLAN unreliable for all users. The second solution is to use multiple queues for service classes, and to do dynamic adaptation of transmission rates and retry limits. The third solution is to use multi-rate multi-channel MAC protocols, as described in the next section.

Multi-Rate Multi-Channel MAC Protocols

Dynamic transmission rate selection is widely used in IEEE 802.11b WLANs to combat adverse wireless channel conditions. However, overall system throughput suffers when stations with different transmission rates share the same physical channel. This phenomenon is another manifestation of the "bad apple" problem, though it is not quite as severe as in the video streaming case.

In our recent work, we are proposing and evaluating a multi-rate multi-channel MAC protocol to solve this problem. This approach assumes a multi-radio WLAN environment. Our approach uses different transmission channels to isolate high-rate stations from low-rate stations. Simulation is used to evaluate the performance of the proposed protocol, assuming four channels and four transmission rates (1, 2, 5.5, and 11 Mbps). Our simulation results show throughput improvements of up to 450 percent compared to the IEEE 802.11b MAC protocol. Our simulations have considered up to 30 hosts, in both static and mobile scenarios. We have also studied static versus dynamic rate assignment strategies for the channels. In all cases, our new MRMC protocol looks promising. To that end, two papers have been written describing this work and are under submission at this time.

Anonymous Network Communication

Anonymous communication is important for certain network applications. For example, sender anonymity

Carey Williamson

is required for applications such as e-voting and e-counseling for victims of abuse, while receiver anonymity may be needed to protect freedom of speech when publishing certain documents on the Web.

There have been several systems proposed for providing anonymous network communication. For example, Mixes provide anonymity by re-routing a message through a series of intermediate nodes, using layered encryption to hide the contents of a message from hop to hop. Broadcasting approaches send each encrypted message to everyone, though only the intended receiver has the key required to decrypt the message. Our team has spent the past two years designing, implementing, and evaluating an anonymous communication scheme. The design of our anonymous communication scheme is based on the Buses protocol from the literature. Buses provide strong mutual anonymity without the overhead incurred by mixes and broadcasting. The Buses protocol uses the metaphor of a city bus with a scheduled route through the network. The bus hides a message's route through the network just like a public transit bus hides a passenger's route through a city.

We have implemented and evaluated this modified Buses protocol in a Linux cluster environment. Several modifications to the original Buses protocol were necessary to protect against replay attacks, to make the protocol scalable, and to make it practical for implementation. To the best of our knowledge, we have created the first practical implementation of any Buses protocol in the literature.

This work is exciting and significant. Our measurement results show that our protocol is a promising alternative for providing strong anonymity with manageable overhead. The potential impact of this work on Internet-based communication is huge.

Two research papers have been prepared related to this work. Both papers have been submitted for possible publication, and are still in the review process. Extending the protocol to wireless ad hoc network environments is the primary challenge for this research.

OBJECTIVES FOR THE NEXT YEAR

The objectives for the next year are to build and maintain a sustainable network measurement infrastructure in the ELISA lab to support our research, to build and evaluate a stadium-scale prototype for wireless video streaming, and to conduct a capacity planning simulation study for TELUS Mobility using our custom-designed traffic models for cellular data networks. These projects will hopefully continue as the Chair undertakes the iCORE renewal process in Fall 2005.

Carey Williamson and some research team members at the 2005 Banff Informatics Summit

RESEARCH TEAM MEMBERS

My research team currently consists of two faculty members, six full-time research staff and eight graduate students (three of whom are co-supervised).

There were several changes in my research staff this year:

- Tianbo Kuang. Tianbo resigned in August 2004 in order to take a new job at Intel in Calgary. Tianbo was a valuable employee for the last three years, doing a lot of research on wireless network measurement, video streaming, and multi-channel MAC protocols. He and I co-authored five research papers in the last three years.
- Guangwei Bai: Guangwei's position with my research group also came to an end in August 2004. Guangwei and I co-authored eight research publications in the last three years, including the work on wireless Web servers and the modeling of Web cache filter effects. Guangwei is still exploring employment options in the Calgary area.
- Nayden Markatchev: Nayden became a full-time graduate student in January 2005, and had to relinquish the ELISA lab manager role that he has handled admirably for the past three years. Nayden was admitted to the MSc program, and has chosen to work with Dr Rob Simmonds on Grid Computing.

Team Members

FACULTY TEAM NAME	ROLE/TOPIC	AWARDS/SPECIAL INFO
Carey Williamson	Team Leader, Wireless Internet	NSERC/iCORE/TELUS Mobility IRC
Anirban Mahanti	Assistant Professor	Multimedia Systems
POSTDOCTORIAL FELLOWS		
Yujing Wu	Wireless, CDMA	Telus Mobility
PHD STUDENTS		
Xiaozhen (Jean) Cao	Wireless Streaming	NSERC IPS, TRLabs Fellowship
Mingwei Gong	Wireless Scheduling	Passed candidacy January 2005
Andreas Hirt (co-supervised)	Anonymous Communication	NSERC CGS and AB Ingenuity
Nadim Parvez (co-supervised)	TCP Modeling	Started January 2005
MSC STUDENTS		
Sean Boyden (co-supervised)	Video Streaming	Province of Alberta Scholarship
Abhinav Gupta	Ad Hoc Routing	AB Ingenuity, finished August 2004
Andreas Hirt (co-supervised)	Network Anonymity NSERC PGS	Finished July 2004
Gwen Houtzager	Web Proxy Caching	NSERC PGS, finished Jan 2005
Alok Madhukar	P2P Traffic Analysis	TRLabs Scholarship
Aniket Mahanti	Web Proxies	NSERC PGS
Dan Munteanu	Network Processors	Finished August 2004
Ian Wormsbecker	Multi-Channel MAC	Heritage Scholarship
Fang (Shelly) Xiao	WLAN Fairness Issues	Finished August 2004

OTHER RESEARCH TEAM MEMBERS		
Martin Arlitt	Network Traffic Measurement	HPLabs, Grid Research Centre
Guangwei Bai	Traffic Modeling	Ended August 2004
Emir Halepovic	Network Traffic Analysis	NSERC CGS for Sept 2005
Gwen Houtzager	Network/System Admin	Started January 2005
Tianbo Kuang	Wireless Protocols	Ended August 2004
Nayden Markatchev	Network/System Admin	Ended December 2004
Hongxia Sun	CDMA, Cellular	TELUS Mobility project
Qian Wu	Network Simulation	Multi-channel MAC

COLLABORATIONS

INSTITUTIONAL AND PROVINCIAL

WIRELESS PILLAR, WESTGRID

At the University of Calgary, my research team and I interact with the TeleSim research group coordinated by Rob Simmonds and Brian Unger. We attend weekly meetings as part of TeleSim, exploring mutual interests in parallel/distributed simulation, high performance computing, and grid computing. I am also a participant in Netera and WestGrid.

I attended the annual general meeting of Centre for Information Security and Cryptography (CISAC), organized by iCORE Chair Hugh Williams. I have registered with CISAC as an affiliated researcher.

I have attended several strategic planning meetings of the so-called “Wireless Pillar” group at the University of Calgary. This group is fostering multi-disciplinary collaboration on wireless research initiatives at the U of C. Several other iCORE researchers (for example, Graham Jullien, Gérard Lachapelle, Jim Haslett) are part of this group, as is CRC Chairholder Michal Okoniewski.

NATIONAL

U OF C, U OF S, CFI, NSERC

My main multi-institutional partnership involves the CFI-funded Experimental Laboratory for Internet Systems and Applications (ELISA), shared by the University of Calgary and the University of Saskatchewan. The bulk of the equipment for the CFI-funded ELISA lab arrived this year. The purchase process was on hold for the last 2 years pending completion of the inter-institutional agreement between the University of Calgary and the University of Saskatchewan.

Research Services completed the inter-institutional agreement in November 2004, after 28 months of negotiations. Purchase orders were issued in December 2004. The ordered equipment has now arrived, with most of it installed and operational at the University of Calgary.

Payment for the equipment has not yet been processed. An additional one-year extension has been sought and received so that my ASRIP account does not expire prior to project completion. The project end date is now March 31, 2006.

The ELISA project is now eligible to apply for CFI Institutional Operating Funds (IOF). The University of Saskatchewan is forwarding the application to CFI, requesting approximately $270K to be shared equally between the two universities. These funds will provide salary and benefits for a full-time lab administrator at each site for three years.

While not a research collaboration in the usual sense, I also served on two national committees for agencies that provide grants to researchers. About two months of my time were devoted to reviewing NSERC grants for NSERC GSC-330 (Computer and Information Science). I reviewed 69 Discovery Grants and 9 Equipment (RTI) Grants, totalling about 1600 pages. I also attended the six-day NSERC GSC meeting in Ottawa in February. This was my first year of a three-year term on this committee. While there is immense academic value in this volunteer service, the time and energy required for this work are substantial. I also serve on the national College of Reviewers for CFI grant applications. I reviewed about five grant proposals this year.

INTERNATIONAL
SIGMETRICS 2005, WWW 2007
My international collaborations focus on upcoming research conferences: The first involves hosting the 2005 ACM SIGMETRICS Conference. Derek Eager (University of Saskatchewan) and I are sharing duties as General Chairs for this conference, which is the premier annual international conference on computer systems performance evaluation. Approximately 150 conference attendees are expected for the conference on June 6-10, 2005. We have selected Banff as the location, with the Banff Park Lodge as the conference hotel. I have applied for and received an iCORE ISPR grant ($10K) to help provide financial support for hosting this prestigious conference. A second activity relates to the World Wide Web (WWW) Conference, which will be hosted in Banff in May 2007. Activities related to WWW 2007, for which I am General Chair, are picking up. I have become a member of the International World Wide Web Conference Committee (IW3C2) executive, as required by the IW3C2. I will be attending an IW3C2 executive committee meeting at WWW 2005 in Japan in May to report on our planning activities for the 2007 conference. With assistance from Carole Carlton at iCORE, we have chosen EventPlan as the Professional Conference Organizer (PCO) for WWW 2007. We are currently negotiating the contract with the Fairmont Banff Springs Hotel. Again, I have applied for and received an iCORE ISPR grant ($10K) to help bootstrap the planning for this large (1000-person) conference.
INDUSTRY
TELUS MOBILITY
My primary industrial collaboration has been with TELUS Mobility in Toronto, as part of my NSERC/TELUS/iCORE Industrial Research Chair in Wireless Internet Traffic Modeling. Hongxia Sun, Yujing Wu, and I visited TELUS Mobility in Toronto in August 2004. We provided Michael Wu with an update on our research progress, and we obtained a CD-ROM of measurement data from the TELUS Mobility network. A significant portion of my research time this past year was spent on network traffic analysis work for TELUS Mobility. Research team member Hongxia Sun and I did most of this work, with some assistance from Yujing Wu and Emir Halepovic. A 40-page final report was provided to TELUS Mobility in December 2004 as a deliverable. The contents of this report are confidential to TELUS Mobility and cannot be described here. We had one meeting with TELUS Mobility this past quarter as well. Michael Wu and Paul Wang visited the University of Calgary on March 17, 2005. They met with me and my research team (Hongxia Sun, Yujing Wu, and Emir Halepovic) to review the project status and next steps for 2005.
TRLABS
A second example of industrial research collaborations is my participation as an Adjunct Scientist at TRLabs Calgary. I regularly attend research staff meetings at TRLabs, and gave a presentation there in December 2004 on multi-channel MAC protocols. Two of my graduate students are funded in part by TRLabs, as part of a new initiative on Home Networking Technologies. PhD student Jean Cao has an NSERC Industrial Postgraduate Scholarship (IPS) with TRLabs as the industrial partner. They supplement her IPS award with a TRLabs Fellowship. She is working on wireless video streaming. MSc student Alok Madhukar holds a TRLabs Scholarship. He is working on Peer-to-Peer traffic classification techniques that can be used by Internet Service Providers in wired or wireless networks.

INTELLECTUAL PROPERTY

The UTI office is currently handling five of our Intellectual Property disclosures from the last few years. These disclosures include Wireless Web Servers, Bidirectional Multi-Channel MAC Protocols, Multi-Rate Multi-Channel MAC Protocols, Hybrid SRPT Scheduling Policies, and Anonymous Network Communication Protocols. To the best of my knowledge, no patents, licenses, or revenue have yet arisen from these disclosures, though several companies have expressed interest in certain aspects of our work. Ian Bell is in regular contact with me on the status of these disclosures.

FUNDING

Carey Williamson's research in his wireless lab is funded by an iCORE Professorship and an iCORE Industrial Chair. This year he has received contributions from CFI ($405K), NSERC (~$218K), ASRA (~$202K) and his industrial partners Telus Mobility and TRLabs ($143K combined). The University of Calgary has also provided $78K this year.

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

M. Arlitt and C. Williamson, "An Analysis of TCP Reset Behaviour on the Internet", *ACM SIGCOMM Computer Communication Review*, Special Issue on the Internet's Vital Statistics, Vol. 35, No. 1, pp. 37-44, January 2005.

A. Mahanti, D. Eager, and M. Vernon, "Improving Multirate Congestion Control Using TCP Vegas Throughput Equations", *Computer Networks*, Vol. 48, No. 2, pp. 113-136, 2005.

G. Bai and C. Williamson, "Time-Domain Analysis of Web Cache Filter Effects (Extended Version)", *Performance Evaluation,* Vol. 58, No. 2-3, pp. 285-317, December 2004.

J. Rolia, X. Zhum, M. Arlitt, and A. Andrzejak, "Statistical Service Assurances for Applications in Utility Grid Environments", *Performance Evaluation*, Vol. 58, No. 2-3, December 2004.

A. Mahanti and D. Eager, "Adaptive Data Parallel Computing on Workstation Clusters", *Journal of Parallel and Distributed Computing*, Vol. 64, No. 11, pp. 1241-1255, November 2004.

T. Kuang and C. Williamson, "Hierarchical Analysis of RealMedia Streaming Traffc on an IEEE 802.11b Wireless LAN", *Computer Communications,* Vol. 27, pp. 538-548, 2004.

REFEREED CONFERENCE PROCEEDINGS

X. Cao, G. Bai, and C. Williamson, "Media Streaming Performance in a Portable Wireless Classroom Network", *Proceedings of IASTED European Conference on Internet Multimedia Systems and Applications* (EuroIMSA), Grindelwald, Switzerland, pp. 246-252, February 2005.

A. Omotayo and C. Williamson, "Multi-layer Analysis of Web Browsing Performance for Wireless PDAs", P*roceedings of IEEE International Workshop on Wireless Local Networks* (WLN), Tampa, FL, pp. 660-667, November 2004.

T. Kuang and C. Williamson, "A Bidirectional Multi-channel MAC Protocol for Improving TCP Performance on Multihop Wireless Ad Hoc Networks", *Proceedings of ACM/IEEE International Workshop on the Modeling and Simulation of Wireless and Mobile Systems* (MSWiM), Venice, Italy, pp. 301-310, October 2004.

A. Gupta, I. Wormsbecker, and C. Williamson, "Experimental Evaluation of TCP Performance in Multi-hop Wireless Ad Hoc Networks", *Proceedings of IEEE/ACM International Symposium on the Modeling, Analysis, and Simulation of Computer and Telecommunication Systems* (MASCOTS), Volendam, Netherlands, pp. 3-11, October 2004.

Y. Li and C. Williamson, "A Hysteresis Model for Web/TCP Transfer Latency", *Proceedings of IEEE/ACM MASCOTS,* Volendam, Netherlands, pp. 167-174, October 2004.

M. Gong and C. Williamson, "Simulation Evaluation of Hybrid SRPT Scheduling Policies", *Proceedings of IEEE/ACM MASCOTS*, Volendam, Netherlands, pp. 355-363, October 2004.

G. Bai and C. Williamson, "The Effects of Mobility on Wireless Media Streaming Performance", *Proceedings of Wireless Networks and Emerging Technologies* (WNET), Banff, AB, pp. 596-601, July 2004.

C. Williamson and N. Kamaluddeen, "Network Measurements of a Wireless Classroom Network", *Proceedings of the 16th International Conference on Wireless Communications* (Wireless 2004), Calgary, AB, pp. 561-570, July 2004.

G. Bai, K. Oladosu, and C. Williamson "Performance Issues for Wireless Web Servers", *Proceedings of the International Workshop on Mobile and Wireless Ad Hoc Networking* (MWAN), Las Vegas, NV, pp. 59-65, June 2004.

BOOKS AND CHAPTERS

A. Williams, M. Arlitt, C. Williamson, and K. Barker, "Web Workload Characterization: Ten Years Later", to appear as a book chapter in *Web Content Delivery*, 2005. Invited.

C. Williamson, "Wireless Web Performance Issues", to appear as a book chapter in *Web Content Delivery*, 2005.

SPECIAL/INVITED PRESENTATIONS

C. Williamson, "Portable Networks", Distinguished Lecture Series, Department of Computer Science, University of Victoria, October 29, 2004. Invited.

C. Williamson and M. Gong, "Simulation Evaluation of Hybrid SRPT Scheduling Policies", Workshop on Multi-Server Scheduling, Carnegie Mellon University, Pittsburgh, PA, USA, April 19, 2004. Invited.

ADVANCED TECHNOLOGY INFORMATION PROCESSING SYSTEMS

ATIPS has built a team of international-class researchers with complementary knowledge and expertise, the effective combination of which leads to the creation of unique and highly imaginative solutions for a variety of applications.

GRAHAM JULLIEN

iCORE Chair
Department of Electrical and Computer Engineering
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The Advanced Technology Information Processing Systems Laboratory at the University of Calgary (ATIPS) leverages highly advanced and emerging computing technologies to conduct research into the development and implementation of a variety of information processing systems, including: high performance digital signal processors, machine vision systems, information security systems, streaming video processors, bio-engineering devices, arithmetic intensive processors, wireless networking components, opto-electronic sensors and processors. ATIPS' research effort is principally concerned with the exploitation of microstructure techniques, including micro-electronics, System-on-Chip (SoC), micro-electro mechanical systems, microfluidics, and sensors, to the benefit of Canadian industry, Canadian health, high technology diversification in Alberta, and the training of highly qualified personnel.

EXECUTIVE SUMMARY

Our fourth year of operation has continued to build on the exciting successes of 2003 as the group begins to reap the benefits of longer-term investment. This year has also seen the groundwork laid for the major thrust of ATIPS 'second term' as we have expanded our research into biomedical applications through new collaborations with international-class researchers in medical science and bioengineering.

In 2004-2005 we achieved the following milestones and successes:

- Successful demonstration of (wireless) transcutaneous power and data transfer
- Successful fabrication of the microneedle array for drug-delivery/blood-sampling - with Micralyne Inc.
- Successful demonstration of a SoC implementation of secure key establishment - with Non-Elephant Encryption Systems Inc. (NE2), and the Centre for Information Security and Control (CISaC – University of Calgary)
- Development of a suite of defect detection algorithms for TDI in-camera processing systems - with DALSA Corp, led by fellow iCORE Chair Hugh Williams
- New implementation and simulation results for an improved hearing instrument architecture using our novel multi-dimensional logarithmic number system - with Gennum Corp.
- New 2D algebraic integer mappings for error-free image and video transforms
- Design and successful demonstration of a novel ultra-low noise Cellular Neural Network (CNN) analog array for signed digit and DBNS arithmetic
- Downloads of QCADesigner have exceeded 3000. Konrad Walus wins the "Research Leaders of Tomorrow" award at the 2004 Alberta Science and Technology Gala in Edmonton
- Lexel™ Array poster wins the Micralyne Award at the 2004 CMC Texpo

Major new multidisciplinary research projects and programs have been initiated in the following areas:

- A $506K NSERC Strategic Grant in collaboration with CISaC and supported by NE2, and General Dynamics Canada
- A ground-breaking new initiative in neuron-silicon interfacing in collaboration with Dr N. Syed of the Faculty of Medicine. This work has great potential for treating neuronal damage and enabling biological neural networks.
- New initiatives in nerve-regeneration, bio-cell ion-channel activation, and wireless patient monitoring with colleagues Dr D. Zochodne (Medicine), Dr V. Birss (Chemistry), and the "Ward of the 21st Century", multidisciplinary project with Dr J.W. Haslett (iCORE Chair, ECE)

New collaborative ties with key academic and industry groups including:

- A new collaboration with the Microelectronics Institute at Tsinghua University, Beijing
- An IP sharing agreement with Semiconductor Manufacturing International Corporation, Shanghai
- Research exchange agreements with GETA (Helsinki), LIRMM (Montpellier), and LIP (Lyon)

Continued collaborative ties with:

- DALSA Corp. (Waterloo, ON): machine vision and imaging systems
- Gennum Corp (Burlington, ON): video processors and hearing instruments
- RCIM, University of Windsor: integrated circuit design
- CMC Microsystems: SoC Research Network (interaction with 26 other universities)
- LIRMM, Montpellier University, France: number theoretic and crypto systems

Infrastructure advancements:

- A technologist has been hired for the Class 100 Integration Facility
- The University of Calgary has provided funding to support the building of a Class 1000 facility adjacent to the Class 100
- ATIPS has secured all funding to support the CFI grant to establish an Integrated Sensor Lab (ISL) and has identified a technician for that facility

Our research has resulted in the creation of a substantial amount of intellectual capital

- 78 publications in journals conferences and books
- 21 contributions to international standards
- One patent awarded, a further six applications filed; Registered a key invention

ATIPS team members have also graduated seven students, with three more defending their theses shortly, and attracted some of the best graduate students interested in our research, to the ATIPS environment. Last year saw the beginnings of the ATIPS team's work on cryptographic implementation systems. This work has grown faster than might have been anticipated and is becoming a major element of ATIPS' research work. The award of a NSERC Strategic Research Grant (in collaboration with industry) will support our continued drive into information assurance and security whilst also making a valuable contribution to ATIPS' growing SoC capability. As awareness of the potential of microsystems design grows, ATIPS' reputation and expertise has supported the development of new collaborations with medicine and bioengineering. This effort has led to a number of proposals and initiatives, including ATIPS' first shared post-doctoral fellow (PDF) with the Faculty of Medicine.

Together with ATIPS' existing expertise in information processing and circuit design, microconvergence and information security will form the core of ATIPS' thrust into new and exciting application areas. By embracing these opportunities, ATIPS strives to maintain its position on the leading edge of advanced technology research.

RESEARCH PROGRAM OVERVIEW

Our research goal is to build and apply our knowledge and expertise to innovate at all steps in the design process.

To support this, ATIPS has built a team of international-class researchers with complementary knowledge and expertise, the effective combination of which leads to the creation of unique and highly imaginative solutions for a variety of applications. These self-directed researchers can be effectively pooled in various combinations to create larger research teams on 'higher-level' system problems.

In our fourth year, we have expanded upon our previous successes and collaborations, starting a number of new biomedical research efforts with members of the Faculty of Medicine. Notable amongst these are two new collaborations with Dr Naweed Syed that are the first projects related to the building of microchips for the manipulation of, and communication with, neurons using electric fields and charge transfer techniques. This work shows great potential for repairing nerve damage.

Some of our specific successes this year include:

- New initiatives in bio-cell research technologies and wireless patient monitoring
- New collaborations with the Microelectronics Institute at Tsinghua University, Beijing, and Semiconductor Manufacturing International Corporation, Shanghai
- Successful demonstration of wireless power and data transfer to an implanted device
- Successful fabrication of a microneedle array for drug-delivery/blood-sampling

- Successful production of a hardware prototype of a secure key establishment system in less than six months; over 20 contributions to international standards
- 78 publications in journals conferences and books
- The first external publications using ATIPS' QCADesigner tool for an emerging nano-technology with application to future circuit design
- Three new research exchange agreements with establishments in Europe

WIRELESS NETWORKS

Digital Signal Processors for Wireless Base-Stations

The goal is to produce single-chip high performance solutions for the very high data rate signal processing required for next generation Gbps wireless networks. In 2004-2005 we completed the design for an advanced single chip DSP using ATIPS' fault tolerant special number representations. The chip is scheduled for a fabrication run later in 2005, using the services of CMC Microsystems, and testing and integration into a board level system will begin once the fabricated chips are received.

System-on-Chip for Low-Power Wireless Platforms

The research goals are to develop low-power platforms for a variety of applications, including secure communications, remote bio-analysis, and multi-media compression systems. Our work this year has successfully demonstrated a prototype hardware implementation of NE2's key establishment algorithm for secure transmission over wireless, wired, and fibre networks. This year we also began a major strategic push to investigate novel cryptographic implementations on custom hardware. This is a three-year collaborative project with Dr H. William's CISaC group and is supported by NE2 Inc.

2004-2005 also saw our first demonstration of (wireless) transcutaneous power and data transfer, initially for the re-creation of gastrointestinal motility. This technology should enable a number of biomedical innovations and one that has already been referenced in a new grant proposal. One application that could benefit directly from this work is a recently initiated project to develop an implantable blood glucose monitor that has the potential to be used in an insulin delivery system for diabetics. The sensor does not require oxygen for its operation, unlike most of previously reported sensors, resulting in improved accuracy and longer-term stability. This latter work is a collaboration between Dr V. Birss of the Department of Chemistry, and Dr Jullien.

Future wireless SoC developments include a new project investigating in-situ real-time patient vital sign monitoring. This is an extension of our long-term ad hoc sensor network project with RFIC iCORE/NSERC Industrial chair Dr J. Haslett and Canada Research Chair Dr M. Okoniewski (Department of Electrical and Computer Engineering, University of Calgary).

Graham Jullien with some of his ATIPS research team members

EMBEDDED SYSTEMS/FAULT TOLERANT SYSTEMS

These systems are broadly defined as those that contain full-custom, field-programmable or processor-based integrated circuits.

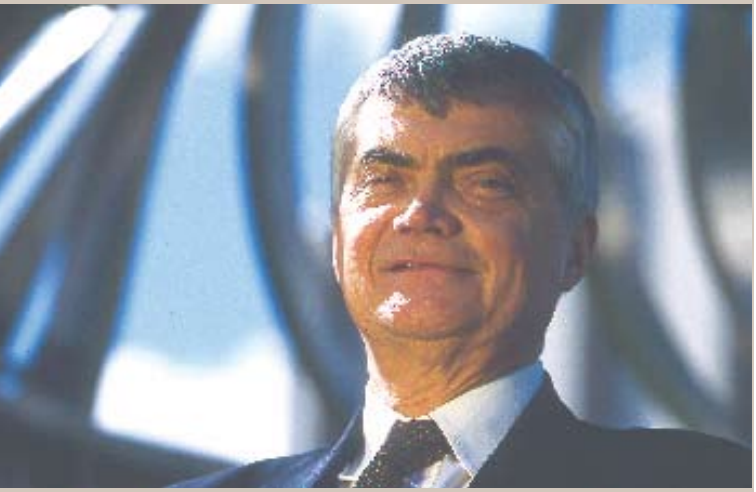
Machine Vision

Our goals and objectives for machine vision are to develop new algorithms and implementation techniques for in-camera processing of moving images obtained from targeted industrial inspection processes. In 2004-2005 we completed a suite of defect detection algorithms and developed FPGA code for their implementation onto camera systems manufactured by DALSA Corp. In addition, we have filed a full patent application on our TDI self-synch algorithm. This year we also demonstrated the potential of plenoptic camera systems.

We have developed two new approaches to the tracking of multiple moving objects and will carry out detailed performance assessments in the coming year.

Hearing Instruments

Our medium-term research goal is to develop next generation embedded systems for completely-in-the-canal (CIC) hearing instruments. This research is being conducted with one of our industrial sponsors (Gennum Corp). In 2004-2005 we refined our MDLNS approach for low-power hearing instrument architectures and successfully demonstrated the performance advantage. We are currently testing a very-low power adiabatic logic chip to further enhance our low-power design capability. Over the next year we will complete testing of this device and continue to investigate the use of adiabatically-powered look-up tables in enhancing the low-power performance of MDLNS implementations.



Graham Jullien

Application-Optimized Arithmetic

Our research goals are to develop application-specific special number representations and arithmetic "custom-fits" to both the algorithms to be implemented and the advanced and emerging fabrication processes used in device construction, such that system performance is optimized. The range of applications for this research encompasses many of our other projects including work on the implementation of arithmetic for cryptography applications and the digital hearing aid processor project.

A number of advances have been made in the employment of our new number systems and some new techniques have been added to our repertoire. We have demonstrated the use of complex MDLNS in performing Fast Fourier Transforms and developed efficient algorithms for performing key cryptographic functions. In the coming year we will take this work and perform in-depth assessment of the performance advantage of these techniques. This work has benefited greatly from our collaboration with LIRMM (Montpellier) and continues to make rapid progress.

Video Processors

The goals and objectives of this research are to increase the efficiency of implementing the compression standards determined by international standards committees, and to take part in the process of defining new standards. We continue to publish a substantial body of work on video processing architectures and error-free encoding algorithms for the MPEG-4 and H.264 standards. This year ATIPS researchers made 21 separate contributions to the definition of these standards. The coming year should see the completion of the ITU-T/ISO/IEC review of our block motion estimation architecture for inclusion in the H.264 standard. Also in development is a generic SoC multimedia platform suitable for handheld devices.

Circuit techniques

Often our investigations into architectures and arithmetic lead us to examine special circuit (transistor-level) techniques and their implementation. Our research objectives are to explore such implementations in order to improve overall system performance. This year saw the completion of the design, fabrication, and testing of the first CNN chip: a successful "proof of concept". The prototype chip performs so

well that we are now designing a new test-jig in order to measure the very low switching noise inherent in the design. Our CNN architectural explorations in 2004-2005 have also produced the first 3-state CNN signed-digit redundant adder and the first logic-free CNN DBNS adder and representation formatter. This latter design has significant promise for crypto hardware that is resilient to power analysis, and other types of side-attacks.

Fault-Tolerant Systems

Our research goals are to produce low-overhead fault tolerant computational systems that take advantage of special number representation properties. In 2004-2005 this technique was used as the key technology in the design of the ATIPS adaptive filter chip for the TRLabs 1.2Gbps wireless LAN project. This chip is currently being readied for submission to CMC Microsystems for fabrication.

ADVANCED TECHNOLOGIES AND COMPUTING WITH NANOTECHNOLOGY

Advanced CMOS System-on-Chip Platforms

Our objectives here are to bring the advantages of SoC design to research projects that require advanced system-level implementation techniques. Our goal is to develop several basic chip architectures, or platforms that can be custom modified to target different facets of our research. These include low-power bio-platforms and high-throughput signal processing platforms. In 2004-2005 we designed a second-generation Lexel™ array chip: the Lexel™ array provides the ability to manipulate, characterize and separate microscopic particles using non-uniform electric fields. We are developing a generic Lab-on-a-Chip platform based on the Lexel™ design. Mr Jeff. Keilman, an ATIPS Masters student, received the CMC Texpo Micralyne Award for his work on the Lexel™ array.

Advanced Image Sensors

Our goal is to develop imagers with enhanced functionality customized for different applications, such as very high-contrast or low-light scenes. By capitalizing on our knowledge of imager physics, circuit design, and custom architectures we aim to find solutions that best meet the needs of the biomedical research community. In parallel, we will continue to develop our portfolio of expertise in Integrated Sensors. This year we demonstrated the capability to apply an invisible "watermark" to digital images in the image sensor chip itself and published work on expanding the dynamic range of imaging sensors.

Microconvergence

Microconvergence refers to the integration of advanced microstructure technologies such as micro-electronics, micro-electro-mechanical systems (MEMS), micro-fluidics, RF-wireless, opto-electronics and photonics. Microconvergence is an integral part of the ATIPS modus operandi and some microconvergent designs are addressed under other headings. Our principal research objectives lie in the integration of these technologies for applications to biotechnology and the health sciences.

The microneedle array for drug delivery and blood sampling – designed in collaboration with Micralyne Inc. – has now been built and early tests show that it will work well. A new initiative begun in 2004 with the Department of Chemistry is the development of a prototype wireless biosensor for continuous monitoring of glucose levels: a possible automatic warning system for diabetics. The sensor could also be used as the front-end of an insulin release system. When complete, the prototype will be used for Phase I Clinical trials.

The Class 100 Microsystems Integration Facility and included equipment, is now being commissioned and a Class 1000 Laboratory will be constructed adjacent to it shortly. The Integration Laboratory is a shared facility among a number of groups with a presence in the University of Calgary's Calgary Centre for Innovative Technology (CCIT) building.

Nanotechnologies

Our research goal is to explore the potential of emerging nanotechnologies that have the most potential for a smooth transition from existing microelectronics design techniques. Quantum-dot Cellular Automata (QCA) can be used to represent the classical deterministic states of '0' and '1' and thus to build computing systems with familiar architectures. As engineers we are interested in exploring the potential of this technology even though commercial fabrication techniques have not yet been established. To do this we have defined a new research paradigm by developing a Computer Aided Design (CAD) tool for a technology that is not yet proven in terms of fabrication. This concept has been well received by the international research community with papers using the tool for analysis already appearing. Both CAD tool downloads and major publications have resulted from this work and the tool will reach its second major release this year. We are currently working on parallelizing the code to take advantage of the enhanced speed offered by multi-processor and grid-computing concepts.

RESEARCH PROJECTS

WIRELESS NETWORKS AND COMMUNICATIONS

Digital Signal Processors for Wireless Base Stations

The TRLabs 1.2Gbps WLAN (wireless local area network) project has continued during this term. ATIPS researchers have designed a single-chip Tbps throughput Digital Signal Processor (DSP) to facilitate the very high data rate processing required. This adaptive filter chip is a low-overhead fault tolerant design that takes advantage of application-optimized number representations developed by ATIPS. As mentioned before, the design is being finalized for fabrication submission through CMC Microsystems, and testing and integration will begin once the fabricated chips are returned. The earlier work on a fault tolerant processor scheme has been published and is being implemented in the design.

System-on-Chip for Low-Power Wireless Platforms

Over the past year, a team from the ATIPS Laboratory has been working with Non-Elephant Encryption Systems (NE2) to apply SoC design techniques to NE2's patented key establishment technique for secure communications. The team has also been developing efficient symmetric encryption algorithms based on the Advanced Encryption Standard. This work is in collaboration with iCORE Chair Prof. H. Williams' Centre for Information Security and Cryptography (CISaC). Rapid-prototyping of the design has progressed much faster than expected with a hardware platform now completed that includes the first architecture for the NE2 algorithm along with a simulator for demonstrating and verifying the design.

The success of this work has supported the joint ATIPS/CISaC award of an NSERC Strategic Grant to investigate "Novel Implementation of cryptographic algorithms on custom hardware platforms", worth $506,000 over three years. This project aims to develop faster hardware/software implementations of commercially used cryptographic algorithms using novel hardware architectures. These protocols will help protect private and confidential transmissions over a variety of media including wireless, fibre-optic, and conventional wired networks. Other SoC crypto work has included the development of a polynomial residue system multiplication technique over GF(pk) and a Montgomery multiplication algorithm over GF(2k).

An exciting development for 2004 was the demonstration of our transcutaneous power and data transfer designs using Radio Frequency (RF) wireless techniques. The initial application targeted for the technology was for the sequenced electrical stimulation of nerves for the re-creation of impaired gastrointestinal motility, for which the electrical power requirements are substantial. To address the problem of providing electrical power inside the human body, ATIPS researchers developed a model to describe the RF transfer of power between an external transmitter and an implanted receiver. This model formed the basis for the design of two transcutaneous inductive links that were successfully used to transfer both power and data, demonstrating the viability of the design and verifying the predictions of the model. This work brings significant technology to the ATIPS laboratory and could enable a number of biomedical devices, such as the implantable blood glucose monitor being designed at ATIPS. A collaborative team from Bioengineering and Medicine have already referenced this work in a grant proposal for measuring bone and tissue forces at the microscopic level.

A new implantable wireless glucose monitor is also being developed, which will be described in the section on microconvergence.

EMBEDDED SYSTEMS / FAULT TOLERANT SYSTEMS

Machine Vision

A suite of defect detection algorithms has been developed. Many of them have been included in a set of FPGA code that can be downloaded into a DALSA Eclipse™ camera. Simulations have also been developed that demonstrate more complex algorithms that can be used in more recent camera models that have an FPGA with a larger number of logic blocks than the model we have used for our experiments. We have published a journal paper on our novel TDI Self-Synchronization algorithm and we have converted the provisional patent (No. 60/481,806) into a full disclosure for patent protection. This work has been recently presented at a meeting with representatives of engineering groups at DALSA.

We have investigated the construction of a 1-D plenoptic camera system for simultaneous capture of stereo pairs on a single sensor. Plenoptic systems offer the potential to passively measure depth with a single sensor. We have had some issues with the mounting of a suitable lenticular array in front of a commercial digital camera sensor, and are currently resolving these in discussion with DALSA engineers.

We have conducted research into the automated tracking of multiple moving objects. As humans we perform this highly complex function routinely when walking down a busy street or driving on the highway.

Machine vision systems currently lag some distance behind this capability. Research at ATIPS aims to change that and this year we have successfully mated merged probabilistic data association (MPDA) with a smoothing particle filter (SPF). The combination of these techniques results in a robust tracking system that effectively tracks targets in a noisy environment. This research is currently being developed for a system that can be used on high manoeuvrable targets such as speed skaters.

We have also developed a new Fuzzy Particle Filter that is more efficient at tracking highly manoeuvrable objects even against a densely cluttered scene. Over the coming year we will conduct a more detailed performance comparison of this novel approach against existing equivalent techniques.

Hearing Instruments

Improvements were made to our MDLNS approach for low-power hearing instrument architectures and the first journal paper was published on difficult operations in the closed MDLNS system using Range-Addressable Look-Up Tables (LUTs) for conversion between binary and MDLNS. New implementation and simulation results for improved architectures have also been accepted for publication. A very-low-power test chip using "Adiabatic Logic" for high fan-in gates has been designed and successfully manufactured. The device is currently under test and the results look promising.

Application-Optimized Arithmetic

One of ATIPS' core strengths has been the ability to 'redesign' arithmetic operations in order to reduce computational complexity, increase accuracy, reduce design times, decrease the silicon 'real-estate' necessary, or improve the fault-tolerance of a design. This 'optimization' of the calculation process is application specific and has yielded considerable benefits and some very novel ways of addressing issues of performance and cost.

MDLNS is an example of one of these optimization schemes that is being considered for Digital Signal Processing (DSP) applications as a means of accelerating the calculations. One application for the MDLNS approach is the Hearing Instrument research highlighted above. In addition, this year we have been able to demonstrate that Complex MDLNS-based arithmetic can perform Fast Fourier Transforms with the necessary floating-point accuracy. Work is now underway to design the necessary chip architecture to exploit the potential performance gains.

A small test chip was fabricated and successfully tested to allow the evaluation of our DRAM programmable base 2DLNS FIR filter architecture. This work capitalizes on the low transistor count of DRAMs but removes the circuitry associated with the refresh problem.

Efficient arithmetic algorithms have been developed for finite fields used in cryptographic applications (mainly Elliptic curve cryptography), including several variants of a modified Montgomery's multiplication algorithm for binary fields GF(2m) and extension fields GF(pk) of small and medium prime characteristic. These algorithms have been published and are currently undergoing in-depth performance assessment in collaboration with colleagues in the Department of Mathematics and Statistics at the University of Calgary.

Continuing the development of ATIPS' double-base number system (DBNS), we have investigated approaches for converting integers to their DBNS representation. DBNS arithmetic requires fewer operations than conventional arithmetic for point and scalar multiplication – offering a distinct advantage in elliptic curve cryptography. The use of continued fraction expansions offers some promise in accelerating the conversion from integer to DBNS and its performance will also be assessed in more depth through the coming year.

In collaboration with LIRMM and ST Microelectronics (France), ATIPS is investigating leak resistant arithmetic as a protective measure against so-called 'side-channel' attacks on secure communications. Also in this collaboration, we have proposed two new number representation schemes (Adapted Modular Number System, Polynomial Modular Number Systems) and efficient algorithms for improving the arithmetic in the ring of integers Z/nZ. A full Residue Number System (RNS) implementation of the widely used RSA public-key cryptography scheme has also been published.

Video Processors and Processing

Video processor work has progressed strongly in the last year, principally focused on architecture contributions to the H.264/MPEG-4 Standards. H.264 offers superb scalability and high quality video compression and processing, and has been adopted as the standard for next generation DVD movie compression.

ATIPS' work on these advanced video codecs has yielded a substantial volume of publishable work on IP blocks for hardware implementations and over 20 contributions to international standards. Published work includes research on two architectures for block motion estimation - the most computationally intensive task in the encoding process. The combined ITU-T/ISO/IEC committee that is defining the H.264 standard is currently reviewing these and a second architecture is in design. The goal of this work is to

alleviate the block motion "bottleneck" obstructing real-time encoding performance. We are developing an FPGA platform suitable for handheld devices.

Additional work has been published on lifted biorthogonal Discrete Wavelet Transform (DWT) architectures, MPEG-4 architectures, a VLSI prototype for adaptive variable length coding, and prototyping for the H.264 transform.

Our work has continued on the use of algebraic integer coding for error-free representation of irrational coefficients used in many video and image processing transforms. This includes the implementation of Daubechie's wavelets, error-free 4x4 DCT encoding, 2D algebraic integers for 8X8 DCT architectures, and a low-power DCT core.

Circuit Techniques

Work on ultra-low noise digital arithmetic circuit design has focussed on a class of analog cellular arrays known as recursive CNNs. These designs will be particularly useful in a mixed signal environment, where digital noise must be kept to a minimum: for example, in the processing of signals from sensitive biosensors.

The prototype chip proposed last year has now been designed, fabricated and tested, verifying the viability of our proposed technique. An on-chip noise measuring circuit block has been developed to isolate the measurement from off-chip noise interference and a special test jig is being designed. This design will be refined as part of the ongoing research.

In 2004-2005, ATIPS published the first papers on the 3-state signed digit CNN , a switching-free DBNS CNN architecture, and an invited paper that highlights our various CNN arithmetic techniques.

In another approach to asynchronous design, a test chip based on digital asynchronous design and test techniques, developed by one of Dr Jullien's students at the University of Windsor, has been fabricated and is currently under test in the ATIPS Laboratory.

Fault Tolerant Systems

Fault tolerance will become increasingly important as technological advances take us into the nanometer realm. Our particular approach to fault tolerance addresses the use of appropriate number representations for computational fault tolerance, which is acknowledged as being more difficult to build into integrated circuits than data communication and storage fault tolerance. In 2004-2005 we used these techniques to design our high throughput adaptive filter for the TRLabs Gigabit LAN project. Upon completion of the manufacture of the chip we will be able to assess and refine our fault tolerant design approach.

ADVANCED TECHNOLOGIES AND COMPUTING WITH NANOTECHNOLOGY

Advanced CMOS System-on-Chip Platform

The ability to manipulate, characterize and separate microscopic particles is tremendously useful in clinical diagnosis, biomedical research, and environmental analysis. While these functions can be performed using mechanical, chemical, and biological techniques, the use of dielectrophoresis (DEP) is seen as a more effective method of achieving these objectives based solely on the frequency dependent dielectric properties of the micro-particles.

ATIPS' work in the field combines dielectrophoresis, electric field sensors, and the associated digital processing circuitry to great effect in the micromanipulation of bio-cells. A poster on the Lexel™ array by Mr Jeff Keilman, an ATIPS Masters student, won the CMC Texpo Micralyne award in 2004 and the latest results from tests on our Lexel™ I array chip were presented at BioCAS 2004. Our second generation Lexel™ II array has been designed and built.

Experimental results obtained on model microscopic particles have verified the ability of the Lexel™ I array to implement interdigitated dielectrophoretic, quadrupole levitation, and travelling wave dielectrophoretic field configurations.

The Lexel™ I array forms the base structure of a bio-analysis Lab-on-a-Chip platform currently under development. A new project on a low-power wireless platform for biosensors was started in 2004 with our first paper on a new DC-DC CMOS charge pump accepted in.

Advanced Image Sensors

ATIPS advanced image sensor work shows considerable promise for applications ranging from biomedical analysis to security to large structure inspection systems. During 2004, ATIPS began the process of combining imaging technology into a number of micro-convergent systems as well as making advances in the technologies required to improve imaging system performance.

Important developments made by ATIPS researchers include enhanced functionalities such as on-chip individual pixel dynamic range control to suppress image 'hot spots' and reveal more detail in high-contrast conditions. ATIPS has also developed an algorithm and chip design that permits the automatic (invisible) watermarking of digital images as they are

captured by the camera. The "first-of-its-kind" prototype device has been fabricated through CMC and the final package is currently being assembled. This type of watermarking can be used to prove ownership and also to provide evidence of tampering with the image file. Enhancements to the algorithm are being investigated and this work may be the subject of a future patent application.

This year we began to investigate enhancing the low-light level performance of CMOS imagers, focusing initially on low-noise analog read-out circuitry. This technology will be very useful for cell-detection in Lab-On-A-Chip systems.

Microconvergence

As has been stated previously, microconvergence is a common feature of many of ATIPS innovations and is now an integral part of our thinking and design planning. As such, some microconvergent innovations will have already been described under other headings.

This year, work began on developing a small wireless camera microsystem, principally for gastro-intestinal inspection, although such a device has a range of potential applications. Current research is focusing on reducing the image data rate required to transmit video from the device and on possibilities for integrating the camera and radio transceiver onto a single substrate.

We are also involved in the technologies associated with MEMS and microfluidics. A recent example of that work is the successful implementation of a novel microneedle array that contains several hundred microneedles on a silicon die just over 1mm on a side. The array uses channels through the die for fluid transport, allowing bio-analysis and other devices to be mounted on the reverse side of the array.

Under development, in collaboration with Dr V. Birss from the Department of Chemistry at University of Calgary, are a new glucose sensor and signal conditioning and processing circuitry designed in the ATIPS Lab. This sensor will provide continuous automatic monitoring of glucose levels for diabetics to replace the current self-test procedures. ATIPS will help to optimize the sensor's performance and design a prototype for Phase I Clinical trials.

Silicon – Neuron Interfacing

We have recently initiated a contact with Prof. Naweed Syed of the Departments of Anatomy and Physiology in the Faculty of Medicine at the University of Calgary. Prof. Syed has created quite a stir in the media with the disclosure that he and a team led by Prof. Dr Peter Fromherz of the Max Planck Institute in Germany, have closed the loop between live neurons and a silicon chip. This work has very important ramifications for future therapies for a variety of diseases and traumas associated with neuronal damage and further possibilities of information processing using biological neural networks.

The ATIPS Laboratory will be continuing the work of the team at the Max Planck Institute by producing large arrays of neuron stimulators and sensors along with information processing systems on single wafers on which networks of neurons may be grown.

Nanotechnologies

ATIPS has continued to focus on Quantum-dot Cellular Automata (QCA) as a promising emerging technology for future integrated circuit design. Significant progress has been made in advancing the art of QCA simulation and design with the release of QCADesigner 1.4, our unique CAD tool for QCA architectures and presently the most advanced tool available for this purpose. Konrad Walus received the "Research Leaders of Tomorrow" award at the 2004 Alberta Science and Technology Gala in Edmonton for this work. The QCA architecture work on the use of majority logic has been published, as has our work on performance comparisons.

Using this tool we have been able to design the first simple processor in this future technology. This processor is the culmination of work conducted over the past year on circuit optimization including the development of a majority reduction scheme targeted at QCA applications. We have determined that one of the original building blocks of QCA, the coplanar crossover will most likely not work in complex circuits and so we have proposed a multilayer QCA design scheme whereby interconnects are crossed over on separate layers of QCA cells.

We are presently incorporating multilayer QCA principles and simulation capabilities into QCADesigner 2.0, which will be released mid-2005. Recent investigations into the device concept called "Split Current QCA" have led us to believe that such a device concept will not work and we are presently investigating other device geometries for implementing semiconductor QCA-like circuits that will be able to operate at current fabrication densities and at room temperatures.

Additional work this year has addressed the design of adder and multiplier structures using QCA elements and will continue this year with new work already begun on interfacing with QCA structures and the continuation of the parallelization program for QCADesigner. This latter development should allow us to efficiently simulate large circuits created with the tool.

2004 is also noteworthy as the year that other institutions began publishing research that used QCADesigner as a key research tool.

RESEARCH TEAM MEMBERS

PARTNERSHIPS AND COLLABORATIONS

Portions of the ATIPS research program are conducted by students at our collaborative institutions: the University of Windsor and the University of Western Ontario. These students are funded by Micronet and NSERC grants and this expanded base allows the ATIPS team to leverage additional resources to add further value to the work of the ATIPS Laboratory. The following represents the most important events and highlights over the past year in terms of research team members and contributions:

Infrastructure And Grants

- The modular Class 100 Integration Room has been installed and populated with equipment. The installation, including the connection of utilities, has been supported by a $250K grant from the University of Calgary's CCIT Building Fund. A technologist has been hired to oversee safety and to commission and maintain the equipment.
- ATIPS' System-on-Chip Laboratory has successfully produced a hardware prototype of a secure key establishment system in less than 6 months – this is a demonstration of the power of modern integrated circuit design tools and appropriate design flows and an outcome of our interaction with the CMC Microsystems' System-on-Chip Research Network (SOCRN).
- A major strategic push to investigate novel implementations of cryptographic algorithms has begun in collaboration with CISaC and is supported by NE2 Inc., and SGI Canada.
- $288K in Micronet R&D awards and matching funds for ATIPS Collaborative projects with Academia and Industry.
- $506K NSERC Strategic Grant for "Novel Implementation of cryptographic algorithms on custom hardware platforms" in partnership with CISaC and supported by NE2 Inc.
- $154.5K NSERC Discovery grants for four ATIPS team members in 2004
- $200K in equipment and operating grants with collaborating researchers
- $60K in silicon allocation (integrated circuit fabrication) from CMC
- QCADesigner, our emerging technologies CAD tool, had over 3000 international downloads in 2004-2005 and work has begun on parallelizing the code for faster processing.

People Successes

- Dr Ivars Finvers has accepted a joint position between the ATIPS Laboratories and the RFIC Research Group (Dr J.W. Haslett, Director), as a Research Associate.
- Dr Chris O'Neill has taken up a part-time position as Strategic Research Manager in the ATIPS Laboratory. This is a new position with the mandate to manage the cluster that has grown around ATIPS and is jointly funded by ATIPS and RFIC.
- Dr Rudolf Potucek has taken up a position as Postdoctoral Fellow in the ATIPS Laboratories.
- Dr Potucek is jointly funded by ATIPS and the Faculty of Medicine.
- Dr Laurent Imbert (France) has had his leave from CNRS (France) extended for a further 12 months.
- Dr Zhun Huang, from the Microelectronics Institute at Tsinghua University, Beijing, has accepted a position in the ATIPS Laboratories.
- Dr Roberto Muscedere, Postdoctoral Fellow supervised by Dr G. Jullien, has accepted a faculty position at the University of Windsor, as an Assistant Professor.
- Mr Minyi Fu, a PhD student co-supervised by Dr G. Jullien, has accepted a position at Gennum Corporation, Burlington, Ontario.
- Mr Venkata Ramanan joined the ATIPS Laboratory for two months as an intern student from IIT, Guwahati in India working on the Lexel™ II Array biosensor project.
- Mr Vadim Milirud transferred to the Masters program at the University of Calgary from Ben-Gurion University in Israel.
- Mr Konrad Walus has accepted an Assistant Professorship at the University of British Columbia.
- Mr Rumi Zhang has accepted a position as a PhD graduate student in the ATIPS Laboratory.

Partnerships And Collaborations

- Key partnerships with academic and industry groups including Gennum Corp, DALSA Corp., and Micralyne Inc. These partnerships have resulted in substantial funding, productive research initiatives, and IP.
- Our partnership with NE2 Inc. has helped us to gain the aforementioned Strategic Grant.

- New partnerships have been agreed with Tsinghua University and Semiconductor Manufacturing International Corporation, in China.
- Partnership with Micralyne Inc. has resulted in the successful fabrication of a novel design for microneedle arrays.
- Four new collaborations have been initiated with members of the faculty of medicine as part of a major new thrust promoting the biomedical potential of ATIPS' microsystems engineering expertise.
- Exchange agreements have been signed with research groups from GETA (Helsinki), LIRMM (Montpellier), and LIP (Lyon).

Team Leader and ATIPS Faculty

NAME AND ROLE	RESEARCH INTERESTS OR TOPIC	OTHER INFORMATION
G. A. Jullien: ATIPS Lab. Director and Team Leader	Integrated Circuits System-on-Chip Computer Arithmetic Signal and Video Processing Machine Vision Neural Networks MEMS, QCA Fault Tolerance	Fellow of the IEEE Director of the Centre for Microsystems Engineering Member of 8 national and international awards and reviews committees Member of the Board of Directors of CMC Microsystems, Micronet R&D and DALSA Corp Invited to edit a special issue of IEEE Proceedings on System-on-Chip 2004-2005 Co-author of Micralyne Award at Texpo 2004
V.S. Dimitrov: iCORE Research Associate	Number Representations Cryptography Digital Signal Processing Large-scale Optimization Parallel Algorithms	PI on a $506K NSERC Strategic Grant Member of the Signal and Image Processing Program Committee for IASTED 2004 Member of the Centre for Information Security and Cryptography (CISaC) Management Board
W. Badawy: iCORE Research Associate	VLSI Architectures System-on-Chip Video Processing Image Recognition Low-power Design VLSI prototyping	IEEE award for notable service and contributions towards the advancement of IEEE and the engineering professions Man of the Year (2004), the American Biographical Institute, NC, USA Program Co-Chair of the 2004 IEEE "International Workshop on System on Chip for Real-time Applications" Technical Co-Chair of the 2004 "International Conference on MEMS, NANO and Smart Systems"
O. Yadid-Pecht: iCORE Research Associate	CMOS Image Sensors Integrated Sensors Smart Sensors Image Processing algorithms & Hardware implementation Micro-systems	IEEE International Conference on Electronics, Circuits and Systems General Conference Chair Deputy Editor-in-Chief of the IEEE Trans. on Circuits and Systems IEEE Circuits and Systems Society - Distinguished Lecturer IEEE Circuits and Systems Society - Achievement Award

Research Associates

NAME AND ROLE	RESEARCH INTERESTS OR TOPIC	OTHER INFORMATION
I. Finvers	Wireless Monitors & Analog Instrumentation for Health Sciences	Joint position with RFIC Research group
J. Yeboah	CNN Analog Arrays for Low-Noise Digital Adder Design: cellular neural networks, transistor circuit design, computer arithmetic, and integrated circuit design	
H. Zhun	Integrated circuit designs for security applications	Partially funded under NSERC Strategic Grant

Postdoctoral Fellows

NAME AND ROLE	RESEARCH INTERESTS OR TOPIC	OTHER INFORMATION
S. Amer	MEMS Modeling and its manufacturability	Fully funded from the MTC
M. El Zewidi	Secure Data Mining	Fully funded from the MTC
A. Fahmy	Security protocols for streaming data	Fully funded from the MTC
L. Imbert	Computer arithmetic, data security and cryptography, application-optimised arithmetic, efficient implementation of cryptographic systems, high speed computing, fault-tolerant algorithms	Visiting CNRS scholar from Laboratoire d'Informatique Robotique et Microélectronique de Montpellier (LIRMM), France.
R. Muscedere	Difficult Operations in Double-Base Number Systems: multi-dimensional logarithms, conversion and arithmetic algorithms, and integrated circuit implementation	Now an Assistant Professor at the University of Windsor
R. Potucek	Neuron-silicon interfacing Dr Potucek is the first joint PDF between ATIPS and the Faculty of Medicine	Joint initiative with Professor Naweed Syed's Neuroscience Research Laboratory
P. Zhang (MEMS)	Bio MEMS, Optical MEMS, MEMS Processes, Integration Facility procedures	$30K Micralyne fabrication grant
W. Zhang (SoC)	Data Stream SoC Architectures, VLSI Design, Integrated Circuit Test, Neural Networks	

PhD Students

NAME AND ROLE	RESEARCH INTERESTS OR TOPIC	OTHER INFORMATION
M. Ahmadi	Plexel Arrays for bio-sensors	eMPOWR (NSERC) Scholarship
I. Amer	New standards for high performance streaming video processor architectures (H.264)	iCORE Graduate Student Scholarship AIF Studentship Nominated for "Best Student Paper" at IEEE Conference on Acoustics, Speech, and Signal Processing, Philadelphia, Pennsylvania, USA, March 2005

NAME AND ROLE	RESEARCH INTERESTS OR TOPIC	OTHER INFORMATION
I.C. Baykal	Defect detection using in-Camera Video Stream Processing: Self-Synchronized TDI, Machine Vision, Line-scan CCD, FPGAs, and Video Processing	Applied for provisional patent for a novel TDI self-synchronization technique for CCD cameras Successfully defended thesis January 2005
J. Cai	Video Streaming platform for multi-stream management	
R. Choudhury	Ridgelet Transforms for image compression	eMPOWR (NSERC) Scholarship
A. Entershari	Flexible on chip DEP Arrays for bio-sensors	eMPOWR (NSERC) Scholarship
J. Eskritt, (Part-time)	Applications of MDLNS with complex bases for quadrature signal processing: computer arithmetic, logarithmic number systems, digital signal processing, integrated circuit design	Also ATIPS Lab Manager
M. Fu	Applications of Algebraic Integers in New Architectures for Video Codecs: multi-dimensional algebraic integers, DCT, VLSI design	Research Centre for Integrated Microsystems: University of Windsor
Y. Ghallab	Sensors for electrical fields in micro-channels	Successfully defended in April 2005. Has accepted a postdoctoral position with the joint ATIPS neuron-silicon interfacing group
S. Hammouda	Analog IP migration	
Y. Ibrahim	Very low-noise Arithmetic Processing Unit using Non-Linear Analog Arrays: CNNs, computer arithmetic, analog circuit design	Research Centre for Integrated Microsystems: University of Windsor Defending in June 2005
T. Mohamed	Streaming video compression standards and algorithms (MPEG-4), Architecture for motion tracking	iCORE Scholarship AIF Studentship
B. Prasad	Lab-on-a-Chip analysis platform, Cell tracking algorithms for bio-sensors	
C. Rahman	Motion Estimation Architectures for H.264 / MPEG-4 Part 10 Advanced Video Coding	eMPOWR (NSERC) Scholarship
A. Razavi	Hybrid CMOS Imagers, plenoptic camera systems	EMPOWR (NSERC) Scholarship
M. Sayed	Embedded memory solutions for video applications	iCORE International Scholarship Strategic Microelectronics Council Industrial Collaboration Award at CMC MR&DCAN (co-authored)
Khan Arif Wahid	Compression transforms, algebraic integers, VLSI architectures	Uof C Graduate Faculty Council Scholarship April, 2003 eMPOWR (NSERC) Scholarship
K. Walus	Quantum Cellular Automata: modeling and simulation of quantum dot arrays, design tool development, split-current QCA	NSERC Postgraduate scholarship eMPOWR (NSERC) Scholarship ASTECH "Research Leader of Tomorrow" award Defends his thesis in August 2005

NAME AND ROLE	RESEARCH INTERESTS OR TOPIC	OTHER INFORMATION
K. Wooding	Cryptography and Network Security, Computational Number Theory, Computer Engineering	Co-supervised with Dr H. Williams, CISaC Partially funded by NSERC & Micronet
J. Wu	Asynchronous Multi-Dimensional Logarithmic Number System (MDLNS)	Transferred from RCIM, University of Windsor

MSc Students

NAME AND ROLE	RESEARCH INTERESTS OR TOPIC	OTHER INFORMATION
A. Chan	FPGA implementations and ECC encryption protocols	Co-supervised by Dr M. Jacobson, Department. Of Computer Science Partially funded by NSERC
I. Chervensky	The use of wavelet transforms in biomedical imaging	Co-supervised by collaborator, Dr Mintchev, Director Bio-Instrumentation Lab Partially funded by NSERC
I. Choi	Bio-Cell analysis system for diagnosis purposes	
J. Doherty	Transcutaneous Powering of an Implantable Stimulator for Re-creation of Impaired Gastrointestinal Motility: transcutaneous power transfer, circuit modeling, data coding, integrated circuit design	AIF Scholarship and travel award. Co-supervised by Dr K.I.V.S. Kaler, Director of the Biosystems Research and Applications Group
L. Fleshel	CMOS wide dynamic range sensors	Transferred from Ben-Gurion University
R. Glabb	Low-power System-on-Chip Platforms: IP blocks, design reuse, wrappers, System-on-Chip & embedded design, Cryptography	SoC Lab Manager, Principal Contact for NE2 Collaboration, Major contributor to Strategic Grant application with NE1, SGI and CISaC Successfully defended thesis in April 2005
S. Hamami	Active Pixel Sensor with Pipeline ADC	Writing-up Will be progressing to the PhD program
J. Hogan	Gastrointestinal Pressure Sensors	
P. Horbal (Part-time)	Adiabatic logic for ROM-Based Architectures: adiabatic circuits, minimized dual-rail switching trees, applications to DBNS and MRRNS processors	ATIPS Webmaster and publicity director
N. Karanwal	Software simulation of Fast Fourier Transforms	Partially funded by NSERC & Micronet
J. Keilman	Lexel™ Arrays for Cell Manipulation using Dielectrophoresis: non-uniform electric field generation, microfluidics, integrated processors	NSERC Postgraduate Scholarship Micralyne Award Winner (Texpo 2004) Defending thesis in June

NAME AND ROLE	RESEARCH INTERESTS OR TOPIC	OTHER INFORMATION
M. Mazur	Interfacing with Quantum Cellular Automata, computer communication, Digital logic design/FPGA programming, Embedded systems/firmware development	
V. Milirud	Wireless CMOS imagers	Transferred from Ben Gurion University (Israel)
G. Nelson	CMOS Imager watermarking	NSERC Postgraduate Scholarship
Y. Qiu	An H.264 compatible hardware/software platform for digital video streaming	
G. Schulhoff	Modelling Quantum Dots on a Computer Cluster: quantum dots, quantum mechanics, QCA, simulation tools, computer clusters	
A. Shaohui	Digital Video Processing	Graduated M.Eng. this year
P. Sheridan	Galois field arithmetic and efficient algorithms for matrix inversion over finite fields and rings	Co-supervised with Dr H. Williams, I Partially funded by NSERC
T. Tam	CMOS Imagers: Analog Noise Reduction, Optimising analogue chain to increase sensitivity	Awarded NSERC PGS M scholarship
R. Zhang	Logic design for Quantum Cellular Automata	Defended successfully in March at the University of Western Ontario. Currently with ATIPS on an AIF scholarship

Other Team Members

NAME	ROLE	OTHER INFORMATION
J. Eskritt	ATIPS Lab. Manager & Administrator for the CCIT SoC Secure Laboratory	Also PhD Candidate
P. Horbal	Technical writer and other publicity functions	Also MSc candidate
J. Nakaska	ATIPS Lab Assistant, Webmaster	Also PhD candidate in the RFIC Group
C. O'Neill	Strategic Research Manager	Part-time

COLLABORATIONS

Over the past year we have developed and maintained numerous important collaborations. Some represent current work and some represent an investment that will enable our research growth and technology transfer activities in the coming years. Of the collaborations listed, some have provided financial support (and/or access to IP) to ATIPS while the remaining will or have enabled access to otherwise confidential IP and knowledge.

UNIVERSITIES AND INSTITUTES

PROVINCIAL	
COLLABORATOR	PIS INVOLVED
Centre for Information Security and Cryptography (CISaC) (U of C) **Department of Mathematics (U of C)** Prof. Hugh Williams, iCORE Chair in Cryptography, established CISaC in 2003 to bring together a multidisciplinary group with a shared interest in cryptography and quantum computing. Drs. Dimitrov and Jullien are members of this centre and Dr Dimitrov also sits on the board of CISaC as the Engineering Representative. A joint project between CISaC and the ATIPS Lab. was started in 2003 with NE2, Calgary, and a major Strategic grant was awarded to CISaC and ATIPS this year, supported by NE2 and SGI Canada.	H. Williams R. Scheidler V.S. Dimitrov G.A. Jullien
Institute for Quantum Informations Science (IQIS, U of C) Growing out of our collaboration with CISaC and NE2, we are currently in discussions that also include Dr Barry Sanders' IQIS group, and General Dynamics Canada. This collaboration is investigating the potential of a major initiative in the field of Information Assurance and Security (IAS) that could form the basis for significant growth in the field of IAS within Alberta.	B. Sanders H. Williams G.A. Jullien J.W. Haslett
Centre for Biomedical Research Engineering (U of C) Collaborations have been initiated with members of this group interested in the use of Microsystems for bio-engineering applications. A joint CSA-CIHR grant application has been submitted.	Jullien Shrive
Department of Chemistry (U of C) We are jointly investigating instrumentation techniques for nano-biosensors and their integration with our low-power SoC bio-platform. A key part of this collaboration is our work on implantable glucose monitors.	Jullien Birss
Departments of Anatomy and Physiology (U of C) We have begun a collaboration with Prof. Naweed Syed of the Departments of Anatomy and Physiology. Prof. Syed has created quite a stir in the media with the disclosure that he and a team led by Prof. Dr Peter Fromherz of the Max Planck Institute in Germany, have closed the loop between live neurons and a silicon chip. This work has vast ramifications for future therapies for a variety of conditions associated with neuronal damage. It may also lead to advancements in information processing using biological neural networks. The ATIPS Laboratory will be continuing the work begun by the Max Planck institute, producing large arrays of neuron stimulators and sensors complete with information processing systems on single wafers on which networks of neurons may be grown.	Syed Jullien
Faculty of Medicine (U of C) A collaboration has begun with Dr Douglas Zochodne of the Faculty of Medicine to look at Microsystems for nerve regeneration. A joint CIHR grant has been submitted.	Zochodne Syed Jullien
Faculty of Medicine (U of C) Dr Jullien has formed an alliance with Dr Henry Duff's research group to explore the potential of microsystems in bio-cell ion-channel activation applications.	Duff Jullien

COLLABORATOR	PIS INVOLVED
Faculty of Medicine, Radio Frequency Integrated Circuits Group (U of C) Dr Jullien has joined a team, led by Dr Bob Sheldon of the Faculty of Medicine, to explore the development of wireless monitoring devices for in-situ real-time cardiovascular measurements. This collaboration will also involve the RFIC group, directed by Dr J.W. Haslett, iCORE Chair, and has close links with the "Ward of the 21st Century" project, for which J.W. Haslett is a principal investigator.	Sheldon Duff Roach Haslett Jullien
Centre for Microsystems Engineering - U of C Faculty of Engineering Researchers The CME was established to support research initiatives in the area of micro- & nano-systems and their integration into novel devices. A series of seminars and workshops were presented over the past year.	Jullien, Spiewak and more than 25 other members from the Faculty of Engineering
University of Alberta Drs Badawy and Moussa continue their collaboration on the development of new designs for micro-pumps for drug delivery. The new micro-pumps will be used to further their work on the iPill, for which they received international recognition in 2003.	W. Badawy W. Moussa
City of Calgary Dr Badawy has been applying his novel work on vision systems to the development of an Active Camera Tracking System for Traffic Analysis. The City of Calgary is contributing $90K/year and also allowing special access to traffic lights and infrastructure.	W. Badawy
NATIONAL	
COLLABORATOR	PIS INVOLVED
CMC Microsystems CMC provides microsystem design tools, and fabrication and information services to 44 Canadian Universities, and Colleges. Dr Jullien has been a member of CMC since 1985. He was on the Board of Directors from 1989-93 (vice-chairman of the Board in 1993) and rejoined the Board in 2001. He is one of 10 principal researchers in the System-on-Chip Research network, funded by a $40M CFI grant. Drs. Badawy and Jullien are lead clients for the IP blocks that were purchased from the CFI funds, and the IP-block authoring suite being developed by a sub-committee of the Technical Advisory Committee. A secure laboratory has been set up in the CCIT building to handle commercial IP blocks in the development of SoC platforMs ATIPS researchers and other users of the ATIPS Laboratory provided over 50% of the posters at the 2004 Texpo, a national CMC workshop showcasing Microsystems research form all Canadian University members. Several CMC members from École Polytechnique and the University of Toronto attended as guests at the ATIPS Lab. retreat, during the iCORE 2004 Banff Summit.	ATIPS Laboratory members Other Canadian university participants in the SOCRN
Micronet R&D (NCE) Dr Jullien was one of the founding members of Micronet, one of the first 14 Networks of Centres of Excellence, and one of only 5 to be funded through the full 14 year life-span of networks in the NCE program. Dr Jullien sits on the Board of Directors, the Steering Committee, and the Coordinating Committee of Micronet. Dr Jullien leads a project between the Universities of Calgary and Windsor that was funded at one of the highest levels in 2003, and the largest funded project in 2004. In addition, Dr Jullien is a co-applicant for a second project at the University of Windsor.	ATIPS W. Badawy V.S. Dimitrov G.A. Jullien, W.C. Miller M. Ahmadi (RCIM U Windsor) Other Micronet participants
RCIM Laboratory faculty, University of Windsor We have a formal association with the Research Centre for Integrated Microsystems and are co-applicants on 2 Micronet grants. G. Jullien currently supervises or co-supervises 2 graduate students. Our area of research is in hearing instruments, MEMS, and signal processors. Dr Jullien is an Adjunct Professor at Windsor.	G. Jullien V.S. Dimitrov W.C. Miller M. Ahmadi
ECE Department University of Western Ontario Collaboration on QCA arithmetic structures, and quantum cellular automata arithmetic and logic structures. G. Jullien was awarded an Adjunct Professorship at Western in order to enhance this collaboration. A co-supervised Masters student successfully defended his thesis in March 2005.	Jullien Wang

INTERNATIONAL	
COLLABORATOR	PIS INVOLVED
Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier, France G.A. Jullien and V.S. Dimitrov, have a strong research association with Dr L. Imbert (CNRS Researcher) and Dr J-C. Bajard (Director of the Department of Fundamental and Applied Informatics). This research focuses on computer arithmetic, cryptography, and fault tolerance. Dr Imbert has received a renewal of his leave from CRNS, France, to spend another year at the University of Calgary. Dr Bajard visited the ATIPS laboratory from March to April 2004, to discuss joint research. Prof. Valerie Berthé, also with LIRMM, visited Calgary for two weeks in 2004 to discuss joint research on the Double-Base Number System and associated Multidimensional Logarithms, discoveries by members of the ATIPS Laboratory. In total, this collaboration has resulted in the submission of five research papers in the past year. A research exchange agreement has also been signed between ATIPS and LIRMM, on the same basis as that described below with LIP in Lyon	G. Jullien V.S. Dimitrov L. Imbert J. C. Bajard V. Berthé M. Robert
Laboratoire de l'Informatique du Parallelisme (ENS) Lyon A research exchange agreement has been signed with LIP to promote collaboration in graduate student training and research. Both parties will offer short-term research internships for graduate internship and exchange students. The training will consist of collaborative research projects between laboratories and supervisors at the two institutions.	J. M. Muller G. Jullien
Ben-Gurion University, Isreal Dr Yadid-Pecht was head of the VLSI Systems Center at Ben-Gurion University (Israel) and is still collaborating on research with the staff there.	O. Yadid-Pecht
Graduate School in Electronics, Telecommunication and Automation (GETA) Helsinki University of Technology Dr V.S. Dimitrov has strong ties with GETA, and was a consultant there from 1997-2000. He has taught short courses at GETA from 1998 to the present. G. Jullien also took part in a short course given in September 2004. The areas of research are DSP, number theoretic techniques and cryptography. An agreement was signed in 2004 for a student exchange program between the two laboratories. This will also facilitate research collaboration between the ATIPS Laboratory and various universities in Finland who are indirectly party to this agreement. The student exchange will allow graduate students to visit each other's research laboratories for a period of about 3 months, and will include taking graduate courses as part of their degree program.	V.S. Dimitrov G.A. Jullien I. Hartimo
Microelectronics Institute Tsinghua University, Beijing Research collaboration with the Microelectronics Institute was initiated by a visit, in August, to Prof. H. Chen, Academic Director of the Institute, and some of his colleagues. We have agreed to work on some areas of security systems that lend themselves to integrated circuit implementations. A recent Ph.D graduate, Zhun Huang, has accepted a position in the ATIPS Laboratory to work on the NSERC Strategic Grant.	Chen Jullien
John Hopkins University, USA Dr R. Etienne-Cummings (Johns Hopkins), specializing in Neuromorphic Engineering, and Dr Yadid-Pecht have co-written a guest editorial for a special issue on Smart Sensors in the Analog Integrated Circuits journal, published in June 2004. They have also co-edited a book on CMOS Imagers for Kluwer Press.	O. Yadid-Pecht R. Etienne-Cummings
University of Texas, Austin Dr Earl Swartzlander, of the Department of Electrical and Computer Engineering, has had strong ties with Dr Jullien's research group over the past 18 years. Dr Swartzlander and Dr Jullien have been involved in the organization of several conferences in the area of array processing and computer arithmetic, and Dr Swartzlander was a plenary speaker at the SPIE Conference in August 2004, co-chaired by Dr Jullien.	G. Jullien E. Swartzlander
University of Louisiana at Lafayette Professor M. Bayoumi, Director of the Centre for Advanced Computer Studies and Head of the Computer Science Department at the University of Louisiana at Lafayette, visited the ATIPS Laboratory and presented a seminar, "Integration: Challenges and Opportunities", on April 16th, 2004. Prof Bayoumi also returned on June 5th to attend the iCORE Banff Summit and to take part in the ATIPS Laboratory panel discussion and to provide feedback to students in the ATIPS Laboratory Retreat. G. Jullien and M. Bayoumi have also been invited as guest editors for a special issue on "System on Chip" in the IEEE Proceedings. This is the flagship technical journal for The Institute of Electrical and Electronic Engineers (IEEE).	G. Jullien M. Bayoumi

For brevity we list other academic collaborations together with contacts and research areas in the following table.

GROUP	CONTACT(S)	FIELD OF STUDY
Centre for Microsystems Engineering (CME)	Dr K. Kaler, Dr A. Budiman, Dr M. Okoniewski, and others	Micro/Nano-systems design & integration
Ben Gurion University	Dr M. Katz	VLSI (Very Large Scale Integration)
University of Maryland	Dr Cohen, Dr Abshire	CMOS Sensors
Qinetiq, Malvern, UK	Dr I. Proudler	Emerging Technologies
UCLA	Prof. M. Ercogovac	Computer Arithmetic
University of Florida, Gainesville	Dr F. Taylor	Real-Time Architectures
Eshraghian Laboratories Pty Ltd, Perth, Australia	Dr K. Eshraghian	VLSI Design, Processor Architectures, emerging technologies
Universita' degli Studi di Trento	Dr Andreas Caranti	Number Representations, Crypto
Notre Dame University, Indiana	Dr Craig Lent	Quantum Cellular Automata
The University of Wisconsin, Madison	Dr M. Schulte	Computer Arithmetic

INDUSTRIAL COLLABORATIONS

COLLABORATOR	PIS INVOLVED
DALSA Corp., (Ontario – head office) Dr Jullien has had a long-term research interaction with DALSA Inc. Dr Jullien helped pioneer the concept of in-camera defect detection in 1990 with J. Roberts of DALSA. This idea, patented in 1995 has resulted in sales exceeding $20M over the past decade. Related research has been supported by Micronet with industrial funding from DALSA (approximately $500K over the past decade with matching funds).	G. Jullien J. Roberts G. Ingram C. Flood M. Miethig
Non Elephant Encryption Systems (NE2) (Alberta) This interaction, started in June 2003, has led to the development of custom hardware, simulators, and rapid-prototyping emulators for a patented NE2 key establishment algorithm that promises to revolutionize secure network transmission. The research team is a collaboration between the ATIPS secure SoC laboratory, CISaC, and a team from NE2. On the back of this success, and with support from NE2 and SGI Canada, ATIPS and CISaC have been awarded a Strategic Grant to continue and expand the scope of the work. In a related sphere this collaboration is also expected to evolve to include one of NE2's partners: General Dynamics – a multi-national corporation interested in security products and services.	G. Jullien V.S. Dimitrov H. Williams R. Scheidler L. Imbert M. Tims B. Mackie
TRLabs, Calgary (Alberta) TRLabs has provided sponsorship to the ATIPS Laboratory since its inception. An intern student was partially supported from TRLabs funding working on signal processing components for an experimental 1.2Gbps wireless LAN during 2004.	G. Jullien, G. McGibney
SGI, Alberta and international We are establishing a close working relationship, investigating software and hardware based cryptography initiatives, through their participation in our Strategic Grant.	G. Jullien V.S. Dimitrov H. Williams R. Scheidler L. Imbert B. Kondruck
Gennum Corporation (Ontario – head office) Dr Jullien has been working with Gennum Corp. since 1994. The initial work, which is still on-going, was in the area of video signal processing (for broadcast quality TV signal processing). Since 1998 our group has worked with Gennum on hearing instrument processors. Since 1994, Gennum has contributed over $700K (including matching funds) to our research.	G, Jullien V.S. Dimitrov D. Salvador D. Lynch D. Simmons X. Liu

COLLABORATOR	PIS INVOLVED
Micralyne Inc., Alberta Micralyne is a fabricator of MEMS and speciality integrated circuits in Edmonton. We have been communicating with the company since the ATIPS Laboratory was established. In 2005 we received the first prototypes of the micro-needle blood-sampling / drug delivery system jointly developed between ATIPS and Micralyne and supported by Micralyne funds. A poster describing our recent research on the Lexel™ Array won the Micralyne Award at the 2004 CMC Texpo.	G. Jullien P. Zhang C. Lumb Y. Loke T. Zhou
SMIC, Shanghai IP sharing with the Semiconductor Manufacturing International Corporation (SMIC), in Shanghai. In August 2004, G. Jullien visited a former research associate, who leads one of the design groups at SMIC, and discussed the possibility of obtaining integrated circuit fabrication in one of their advanced processes. Discussions are currently in progress, and a pilot chip design in a selected SMIC process will be started in 2005.	G. Jullien W. Luo
Other industrial contacts We have several other industrial contacts as follows: Qinetiq, UK, (formerly the Royal Signals and Radar Establishment). We have had strong interactions with Dr J. McWhirter, FRS, Dr I. Proudler, and Dr R. Walke in the area of array processors for DSP in the past. Dr Jullien will be visiting Dr Proudler in May 2005 to discuss QCA and QCADesigner. Dr Dimitrov has served on the advisory board of iPROS, a Toronto based start-up in the area of high performance arithmetic for communication systems.	ATIPS Laboratory personnel, and other industrial teams

INTELLECTUAL PROPERTY

TYPE OF IP AND ATIPS MEMBER	TITLE/NAME	STATUS
PATENTS		
Yadid-Pecht	"Optical image using a method for adaptive real-time expanding of the dynamic range"	Approved December 14, 2004 US Patent No. 6,831,689
Badawy	"Mesh Based Frame Processing And Applications"	Filed May 4, 2004 Canadian Patent Application, No.: 2466247
Badawy	"Mesh Based Frame Processing And Applications"	Filed May 7, 2004 United States Patent Application, No. 10/840,433
Ghallab & Badawy	"Imaging System"	Filed July 23, 2004 United States Patent Application, No. 10/896,867
Badawy	"Video Based Monitoring System"	Filed July 29, 2004 United States Patent Application, No. 10/898,952
Mintchev, Kaler, Yadid-Pecht	"Integrated Esophageal Pressure, pH and Bolus Transit Sensor"	Submitted 2004 United States Provisional Patent (Sandhill Scientific – UTI)
Dimitrov & Jullien	"Efficient technique for Elliptic Curve Cryptography computations using a special form of the Double Base Numbering System"	Filed December, 2004 United States Patent Application, No. 60/481,806
INVENTIONS		
Baykal & Jullien	"Synchronization of Time Display and Integration Cameras"	Filed April 21, 2004 Full patent submission filed April, 2005 United States Provisional 60/521,414

FUNDING

This year Graham Jullien and his team received funding from NSERC (~$591K), and the University of Calgary ($577K) to support his lab's exciting new research in biomedical engineering. In addition, government consortiums (CMC and Micronet) have contributed ~$274K, with another ~$258K coming from several industrial sources such as GCE Market, DALSA, Gennum, Micralyne, Sandhill Scientific, and Intellisense.

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WIRELESS SCIENCE AND TECHNOLOGY INITIATIVE

The main thrust of the research program is to develop new and novel devices for the next generations of wireless products, of interest to the industrial sponsors of TRLabs, and to the wireless community in general.

JAMES W. HASLETT

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The Radio Frequency Integrated Circuit (RFIC) Design Group at the University of Calgary conducts research into the design of novel circuits to facilitate complete "radio-on-a-chip" systems for a variety of new applications, such as next generation cell phones, wireless local area networks and personal area networks, wireless ad hoc self-organizing sensor networks for medical applications, and a special application relating to a next generation radio telescope.

EXECUTIVE SUMMARY

The RFIC research group utilizes a variety of technologies, including deep submicron monolithic integrated circuits, MicroElectroMechanicalSystems (MEMS), System-on-Chip (SoC), and sensors, to design new wireless communications devices and systems. Our goal is to enable Albertan and Canadian industries to attain a competitive advantage in world markets such as Health Care and Environmental Monitoring. The research activities of the group are highly interdisciplinary, resulting in the training of highly qualified personnel with the expertise needed to design, develop, project manage, train, and implement these types of systems in industrial contexts.

In 2004, the third year of the Chair program, an outstanding team of academics, post doctoral fellows (PDFs), research associates and graduate students with expertise in high frequency analog, and high speed digital integrated circuit design, targeted at wireless communications circuits and systems, worked to achieve the goals of the RFIC Industrial Chair Program. The completion of the team has led to an exciting expansion of research directions and collaborations that include three major new collaborative research projects:

- A wireless patient vital sign monitoring initiative with the Calgary Health Region and the Faculty of Medicine at the University of Calgary. This initiative also introduced a new medical device industry partner to the research group: Associated Health Systems Inc. of Edmonton.
- An ultra low power wireless sensor platform for medical data that builds on collaborative links between the University of Calgary, McGill University, Carleton University and the University of Alberta.
- An ultra low noise amplifier design initiative for radio telescopes, with NRC's Dominion Radio Astrophysical Observatory in Penticton, BC.

In 2004, our research program resulted in 48 publications, including publication or acceptance of 5 journal papers describing new state-of-the-art fabricated and tested RF integrated circuits, the granting of 2 patents, 27 conference proceedings papers, 11 workshop presentations, and 2 short courses to industry.

During the reporting period over $1.6M in grants, scholarships and other contributions accrued to the research team, in addition to iCORE funding. This included substantial infrastructure support from CMC Microsystems (formerly the Canadian Microelectronics Corporation), which contributed IC design software and other infrastructure in support of the microelectronics program in Electrical and Computer Engineering, and also included substantial financial support from the University of Calgary to help develop the new Advanced Microsystems Integration Facility in the Calgary Center for Innovative Technology. An NSERC equipment grant was received to add fabrication equipment to our Advanced Microsystems Integration Facility (AMIF). The research team held six NSERC postgraduate scholarships (two were prestigious Canada Graduate Scholarships) with supplementary iCORE

scholarships, and one post doctorate fellow received an NSERC Post Doctoral Fellowship during 2004.

RESEARCH PROGRAM OVERVIEW

The Research Team

After three years of operation, a very strong research team has been assembled, well trained in the art of sophisticated analog and digital RF integrated circuit design for wireless communication systems. The team, consisting of Dr Haslett, Dr Sebastian Magierowski, six PhD and ten MSc students, two Post Doctorate Fellows, and two PhD research associates, has won several national and international awards for research in the past year.

Research Partners

The Chair Program is supported by industry via the TRLabs Industrial Research Consortium, by the provincial government through the iCORE program, by the federal government through the NSERC Industrial Research Chair Program, and via substantial support from the Dean of Engineering and the University of Calgary senior administration. We also partner directly with other research chairs at the University of Calgary, with local and national industrial firms, with the NRC Dominion Radio Astrophysical Observatory in Penticton, with the Faculty of Medicine, with the Calgary Health Region, and with several other Canadian universities on a variety of wireless communications projects.

Jim Haslett

The RFIC research group, as part of the ATIPS laboratory cluster, is a member of the CMC's System-on-Chip Research Network, headed by iCORE chair Dr Graham Jullien. This network is funded by a large CFI grant that has brought the technology of System-on-Chip design to participating Canadian universities over the past two years.

Major Research Directions

The main thrust of the research program thus far has been to develop new and novel devices for the next generation of wireless products of interest to the industrial sponsors of TRLabs and to the wireless community in general. That goal has been achieved, and the team is now in a position to apply its expertise to a variety of exciting new research projects.

A major thrust over the next year will be to apply the knowledge we have gained over the past three years to the biomedical and radio astronomy fields, as well as continuing to work with industry to address difficult issues in next generation wireless communications product design. Over the long term, we will work with our partners to design entirely new devices based on the integration of disparate technologies in our new Advanced Microsystem Integration Facility (AMIF), particularly for applications in health care. In the process, we expect to design new wireless communications systems that will find application in a host of other areas, from environmental sensing to home technologies.

RESEARCH PROJECTS

Building on the opportunities that have arisen in the past year, the 2005 research program will focus on the following key areas:

WIRELESS TRANSCEIVER DESIGN (HASLETT)

Realizing Fully Monolithic RF Wireless Transceivers in CMOS Fabrication Technology

The major challenge facing the wireless industry at present is to economically realize all required transceiver circuit functions on one silicon substrate, and to provide programmability to accommodate the various transmission standards encountered. This will reduce the cost of production very significantly, as well as miniaturizing the circuitry. Miniature low power circuits will drive the development of many new applications such as the biomedical industry. While single chip radios have been achieved in some systems such as Bluetooth, which has relaxed speci-

fications, much remains to be done in higher performance applications.

Our research goals in this area are to design on-chip circuitry that will enhance the performance of on-chip passive elements, such as inductors and capacitors, which are key components of wireless transceivers and whose poor performance characteristics prevent the achievement of fully integrated systems at this time. Next steps include the design of circuits that will self-tune the elements to overcome the effects of manufacturing process variations, and finding ways of improving noise performance and linearity.

Designing Ultra Low Power Wireless Transceivers for Ad Hoc Sensor Networks

Our goals in this project are to design a series of transistor-level building blocks to address a major future industry thrust — the achievement of ultra low power or self-powered miniature single chip radios. These will then be employed in a wide variety of applications, from smart clothing to medical monitoring to environmental sensing. The circuits all fall under the heading of "smart dust", which is getting a great deal of attention in the media in recent months. During the past year, we have been working with Dr Okoniewski's CRC research chair group to marry his high quality MEMS inductors and capacitors to oscillator circuits designed by our group to facilitate the design of very low power circuits for the miniature radios. We have also been working with Dr Kris Iniewski at the University of Alberta to investigate the use of quasi-floating gate CMOS digital circuits to achieve very low voltage digital signal processing capability, and with Drs Christian Schlegel and Vincent Gaudet at the University of Alberta to incorporate their novel very low power analog decoder circuits into the receiver chains. Additional collaborations will move this research forward in the coming year.

Medical Patient Vital Sign Monitoring

The goals of this project are to design a low cost, low power or self-powered wireless medical device sensor technology platform (WISe-PAC) that can be connected to new sensors, also designed by the group, to measure medical patient vital signs and transmit to and receive from, a base "mote". The base station mote, also mounted on the body, will be part of a commercial wireless ad hoc, self-organizing sensor network that will enable centralized data collection. The platform will be mounted on various and multiple locations on the patient's body depending on the monitoring application sought (for example: temperature, heart rate).

During the past year, a basic system has been constructed with commercial ad hoc wireless sensor network hardware, combined with custom temperature, heart rate and blood oxygen sensors, to test the proof of concept in the hospital environment.

In the long term it is expected that WISe-PAC could be integrated into diverse biomedical devices. In the short term it will be integrated and tested in a body temperature measuring smart band-aid - dubbed

Jim Haslett and some research team members – the Wireless Cowboys!

electroplast - currently being developed by one of the team. The electroplast has been identified as a key tool in the medical arsenal by our medical colleagues in the Faculty of Medicine and at the Calgary Health Region (CHR), and will provide important advanced warning and monitoring capabilities. Once proof of concept has been achieved, we foresee designing other patient vital sign monitoring devices for use in the medical environment. The team has a unique opportunity to design and test the platform and the electroplast in a working high technology experimental hospital ward environment, the newly constructed "Medical Ward of the 21st Century" at Foothills Hospital (Calgary, Alberta).

Designing Building Blocks for Fully Programmable Digital Radios

Radio receivers that perform analog to digital conversion closer to the antenna and do most of the signal processing in the digital domain are known as digital receivers. Digital receivers are desirable because they can be more easily re-configured for multi-standard operation, can facilitate performance improvements by using digital filters for signal processing, and can potentially realize savings in chip area, power consumption and cost.

The goals of this project are to design a very small footprint, low power analog to digital converter, first for use at intermediate frequencies, and eventually at RF frequencies, to achieve A/D conversion as close to the antenna as possible. During the past year, we have designed an ultra small 6 bit converter capable of 500 megasamples per second, based on "time to digital" techniques. A second circuit, that will convert analog signals to time signals, is being designed. During the next year, we will combine these circuits with a new sub-sampling mixer front end designed, fabricated and tested during the reporting period by one of our researchers, to achieve a complete digital receiver.

Circuits for Optical Fiber Communication Systems

The goals of this project were to design a fully integrated RF logarithmic compression amplifier, along with a Hilbert Transformer and several other components, to reduce problems created by a phenomenon called chromatic dispersion in optical fiber networks, which causes destructive interference and loss of data in long haul fiber communications systems. During the past year, a working monolithic Hilbert transformer was achieved in a Silicon-Germanium BiCMOS fabrication technology. Combined with a monolithic logarithmic compression amplifier previously designed and patented by the group, the new chip was tested successfully in an actual long haul fiber system. This project is now essentially complete.

Ultra Low Noise Amplifiers for Radio Telescopes

The international astronomy community is embarking on a project to construct the largest centimeter wave radio telescope array ever built (one million square meters, called the SKA for Square Kilometer Array,) which will have a transformative impact on cosmology and other research areas. Through the National Research Council Herzberg Institute of Astrophysics, Canada is now developing one of the leading designs for the array elements. We are working with researchers at the NRC Dominion Astrophysical Observatory, and with others across Canada, and at the University of Calgary, to design the front end low noise amplifier for the antenna feed array elements. The requirement is to design an amplifier that can be tied into each of the elements on the experimental 10,000 element Vivaldi antenna feed array, with extremely low noise figures at room temperature. During 2005, we have been developing an optimization theory for a particular amplifier configuration, to understand the best achievable performance with integrated circuits. Goals for the coming year include the study of different topologies and fabrication processes, and a study of discrete devices that may allow us to achieve the target specifications.

SMART ANTENNA COMMUNICATION SYSTEMS (MAGIEROWSKI)

CDMA/SDMA Indoor Wireless Base Stations

The goals of this project are to design the key building blocks of a digital CDMA/SDMA demodulator (including adaptive beam-former and adaptive data correlator) in production-grade integrated circuit technology. It is also intended to quantify the performance necessary of the radio's analog integrated circuitry.

Over the past year, we have begun to investigate the manner in which CDMA and SDMA can be connected in a single digital communication module (the base-station of an indoor wireless network) to form the demodulator components of the transceiver. A key goal in the early stages of this work is to determine (via simulations) the number of users that can be serviced by the CDMA/SDMA radio in a realistic indoor wireless environment. Quantifying the hardware burden (both analog and digital) imposed by this approach is the first step of the project. The ultimate goal is to design and fabricate custom digital chipsets that can be interfaced to analog electronics and antenna arrays to realize a complete CDMA/SDMA transceiver.

On the analog side, we are concerned with determining the minimum resolution needed in the analog-to-digital converters to sustain reliable CDMA/SDMA data delivery. Also, the SDMA algorithm under consideration is particularly sensitive to the linearity of the analog radio-frequency (RF) electronics (the front-end) interfaced to the antenna. Thus, a major objective is to quantify the necessary front-end circuit requirements needed to accommodate the SDMA component.

RF Front-Ends for Smart Antenna Transceivers

This project is focused on the design of low-power fully-integrated RF transmitters and receiver chains intended for statistical beam-forming radios (that is; smart antenna transceivers).

Multi-element antenna arrays are arguably the defining component of multi-input-multi-output (MIMO) wireless systems (that is, systems possessing improved spatial resolution properties). Incorporating arrays in radio communicators promises a substantial improvement in the security and data handling capacity of wireless networks. However, interfacing the arrays to digital communicators presents a tremendous burden on the RF electronics. The crux of the problem rests with the need for a separate RF chain of amplifiers and converters for each component of an array.

To make the statistical beam-forming approach feasible in commercial applications the power consumption and form factor of the interfacing RF electronics must be minimized. The next year's focus will be integration of multiple (identical) transmit and receive chains on one chip. Since this work falls within the scope of the CDMA/SDMA project described earlier, the architecture of the front-end is expected to be greatly influenced by the system-level consideration.

Antenna Arrays for Digital Communicators

This project is focused on developing antenna arrays suitable for statistical beam-forming radios. It intends to exploit micro-fabrication techniques to build periodic structures with engineered electromagnetic properties.

Transplanting board-level antenna array architectures designs to the wafer scale by employing microfabrication techniques is a contemporary challenge for the research community and the subject of this research objective.

Millimeter Wave Parametric Integrated Circuits

The goals of this project are to design and fabricate millimeter wave amplifier and frequency converter circuits for ultra-low-noise signaling applications. Parametric circuits rely on energy storage circuit elements to couple energy from a harmonic energy source to an output under the control of a low power input. These functions constitute a basic amplifier circuit. The main benefit of the parametric approach is that the switch (the storage element) it uses to couple source energy to the output is a very low noise component — unlike the case with standard transistor circuits. Thus, parametric circuits are well suited to ultra-low-noise situations. Further, they are capable of extremely high gains.

Although the concept of parametric circuits is well know in the microwave systems community it has generated almost no interest among integrated circuit designers. This project attempts to bridge the two fields. An immediate benefit of doing so is the availability of high-quality energy storage elements in modern integrated circuit technologies. These components hold promise for improving the amplification and noise properties of parametric circuits as well as allowing unique parametric amplifier configurations.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

Team Leader

NAME	ROLE/TOPIC	AWARDS
Dr J.W. Haslett	Team Leader and Research Chair	Elected Fellow of the Canadian Academy of Engineering, March 2005
	Research interests include analog and digital integrated circuit design in a variety of fabrication technologies for applications in wireless communication systems, biomedical devices, and instrumentation.	

Faculty Team Members

NAME	ROLE/TOPIC
Dr Sebastian Magierowski	New Academic staff member, hired as part of the NSERC Industrial Research Chair program. Research interests include theoretical and practical behavior of RF wireless transceiver building blocks, and smart antenna communication systems. Joined the group from the University of Toronto in 2004
Dr Abdel Yousif	Research Associate High performance digital signal processing systems and architectures for digital radio Seven year design history at Intel, working on the design of the Pentium P4 processor
Dr Ivars Finvers	Research Associate Precision high performance analog CMOS integrated circuit design. Ten years of industrial experience at Nortel, Novatel and SiWorks. 17 teaching and research awards during his career
Majid Aghtar	Research Associate Ultrawideband communications systems integrated circuit component design. MSc degree from Iran, joined in 2004
Dr John McRory	Company Scientist, TRLabs RF designer with extensive industry experience and particular expertise in Power Amplifier Design. Adjunct Professor, University of Calgary
Dr Bob Davies	Company Scientist, TRLabs Optical fiber communications system specialist
Dr Grant McGibney	Company Scientist, TRLabs Wireless communications systems expert. Adjunct Professor, University of Calgary

Post Doctoral Fellows

NAME	ROLE/TOPIC	AWARDS
Dr Vijay Devabhaktuni	Neural networks applied to microwave systems, self organizing ad hoc sensor networks	NSERC Post Doctoral Fellow
Dr Ahmad Chamseddine	High frequency circuit design, in the 50 GHz range Self tuning impedance matching networks for antennas, and passive millimeter wave systems for object detection with applications such as automotive anti-collision systems.	PhD from France, joined in 2004

PhD Students

TEAM MEMBER	ROLE/TOPIC	AWARDS
Chris Holdenried	Novel RF integrated circuit design for optical data transmission systems. Now working at Snowbush Electronics, Toronto Canada.	NSERC PGSB and iCORE scholarships, Analog Devices Inc. Outstanding Student IC Designer Award, presented at the 2005 International Solid State Circuits Conference (ISSCC February 2005) in San Francisco (award amount $1500.00 US). Dean's Research Excellence Award.
Holly Pekau	Sub sampling mixers and high speed data conversion circuits for RF transceivers.	Five years industrial IC design experience at Analog Devices and IBM in the USA. NSERC PGSB and iCORE scholarships. Analog Devices award as above, 2004. Dean's Research Excellence Award.
Leo Belostotski	Ultra low noise amplifier design, working with researchers from the NRC Dominion Radio Astrophysical Observatory in Penticton, on a proposed next generation Radio Telescope.	Five years industrial experience designing RF wireless communications circuits with Murandi in Calgary, NSERC Canada Graduate Scholarship (CGS) and iCORE Scholarship, Dean's Research Excellence Award.
Josh Nakaska	RF monolithic filter design, and automatic self-tuning circuits for on-chip filters.	NSERC PGSB and iCORE Scholarships, Dean's Research Excellence Award
Rob Randall	Fully integrated high linearity CMOS Power Amplifier design.	Held NSERC PGS B and iCORE scholarships, and is now funded by TRLabs scholarship and the IRC chair program.
Ahmed Youssef	Design of ultra low power transceivers for wireless ad hoc networks.	MSc from Ain Shams University, Cairo Egypt, funded by the IRC chair program.
Ken Townsend	Low power CMOS RF transceiver building blocks for applications in wireless sensor networks. This involves the mating of tunable MEMS inductors and capacitors (developed by Dr Okoniewski's group) to standard CMOS circuitry, to achieve low power. The work is part of a national research collaboration with researchers at Carleton, McGill, and the University of Alberta, targeted at designing a low power wireless sensor network platform for medical applications.	NSERC Canada Graduate Scholarship (CGS) and iCORE scholarships, Dean's Research Excellence Award

MSc Students

TEAM MEMBER	ROLE/TOPIC	AWARDS
Jim Kulyk	Transformer based Q-enhanced CMOS monolithic RF Filter Design.	Former PMC Sierra employee, Saskatoon, Sask. Funded by TRLabs Scholarship and IRC chair program. $3000 Strategic Microelectronics Council of ITAC Design Award for Industrial Collaboration, September 2004
Damon Holmes (co-supervised with Dr R.H. Johnston)	Pulse Density Based RF Power Amplifiers. Graduated March 2005, Now working at Nortel in Calgary.	NSERC PGSA and iCORE scholarships. Dean's Research Excellence Award

NAME	ROLE/TOPIC	AWARDS
Cavell Li (part time MEng program)	Simple, low power GPS receiver chain for ad hoc wireless sensor networks, in CMOS technology. Currently working at Wi-Lan in Calgary	RF board designer with many years of industrial experience in Calgary
Michael Chen (co-supervised with Dr Sebastian Magierowski)	Low phase noise RF CMOS VCO's, for applications in ad hoc sensor networks and other high performance wireless transceivers.	
Steven Zhai (co-supervised with Drs. Sebastian Magierowski and Ed. Nowicki)	Low power medical sensors for the ad hoc wireless sensor network project with Foothills hospital. He has successfully interfaced a commercial blood oxygen/ heart rate sensor to the wireless ad hoc sensor network, for patient vital sign monitoring.	
Howard Chan (Supervised by Dr Magierowski)	RF MOS parametric converter/amplifier design, and mm-wave integrated conversion circuits.	
Robert Salmond (Supervised by Dr Magierowski)	CDMA/SDMA smart antenna transceiver. His contribution will concentrate on low-power RF front-ends.	
Jean-Francois Bousquet (Supervised by Dr Magierowski)	CDMA/SDMA smart antenna transceiver. His contribution will focus on data converters and timing.	
Vijay Ramachandaran (Supervised by Dr Magierowski)	CDMA/SDMA smart antenna transceiver. His work focuses on the digital adaptive beamformer and code autocorrelator.	

Others

TEAM MEMBER	ROLE/TOPIC	
Mike Seto, Jennifer Hum, Eric Tong and Jason Ho	These senior undergarduate students worked on a two academic term 4th year team project course project in Fall 2003–Winter 2004. The project involved the design of a server based high quality of service wireless audio system for the TRLabs home technologies initiative, using the IEEE 802.11a wireless standard.	
Brian Herrler and Alain Maillot	Designed readout and display software for patient vital signs in the Ward of the 21st Century, now on internship off campus.	
Malcom Stagg	Malcom Stagg is a grade ten student at the Calgary Christian School, who has been working with the research group to design an integrated circuit for 3-D image processing. This exceptional student has just won several awards at the March 19, 2005 Calgary Science Fair.	Calgary Science Fair gold medal, Nortel Networks Innovation and Technology Award, and the Noel Bourget Auto-Trol Technology award, also chosen by the Youth Science Foundation as one of eight people on Team Canada to go to the Intel International Science and Engineering Fair in Phoenix, Arizona from May 8–15, 2005.
Ian Steiner (intern) BSc	Adaptive Filter for WLAN	Graduate Studies, University of Calgary

COLLABORATIONS

PARTICIPANTS	NATURE OF COLLABORATION
PROVINCIAL	
Dr Graham Jullien	Establishment of the CCIT Advanced Microsystems Integration Facility, design of biomedical sensors and low power digital circuits for patient vital sign monitoring in the Medical Ward of the 21st Century.
Dr Michal Okoniewski	Self-configuring antenna systems and RF MEMS; we have designed and fabricated a self-tuning impedance matching system, working in the GHz range that uses a genetic algorithm and a series of programmable switched tuning stubs in a transmission line to achieve the impedance match automatically. We are also mating MEMS high quality inductors designed by Dr Okoniewski's group with CMOS RF circuitry integrated by our research group, to achieve low noise, low power RF circuits.
NATIONAL	
RFIC Group, UofC, Dr Christian Schlegel, UofA, Dr Calvin Plett, Carleton University, Dr Mourad El-Gamal, McGill University, Dr John Conly, Foothills Hospital and Faculty of Medicine, UofC, Carol Gray, Calgary Health Region.	We are working on proof-of-concept of a wireless self organizing sensor network for patient vital sign monitoring in the Foothills Hospital "Ward of the 21st Century". A prototype system for measuring patient temperature is working in our lab. The national collaborative research project involves the design of a wireless low power SOC platform for acquiring and securely transmitting sensor data for medical patient vital sign monitoring.
NRC Dominion Astrophysical Observatory, Penticton, BC	We are designing the front end ultra low noise amplifiers for a proposed next generation radio telescope. This research effort involves researchers and industrial companies across Canada.
INDUSTRIAL	
TRLabs	TRLabs provided an office to the Chair, student offices, scholarships and computers, and access to a sophisticated RF test laboratory. Staff scientists work with the chairholder and the research group on an ongoing basis.
PMC Sierra, Burnaby, BC	Dr Haslett has been providing RFIC training courses to PMC employees at the Burnaby location. This will be extended to the PMC employees in Eastern Canada and the USA in 2005.
Associated Health Systems, Edmonton and Vancouver	Recently established a collaboration with Associated Health Systems Inc., an Alberta based medical device company, and are pursuing an NSERC Strategic Grant with them.

INTELLECTUAL PROPERTY

PATENTS ISSUED	CANADA	U.S.	OTHER
C. D. Holdenried, J.W. Haslett, J.G. McRory, and R.J. Davies, "Branch Logarithmic Amplifier and Logarithmic Amplifier Delay Circuitry", US Patent number 6,734,712 B2 issued May 11th, 2004.		X	
J.W. Haslett , B. A. Georgescu, H. Pekau and J. McRory, " Monolithic Transformer Compensated Circuit", US Patent number 6,822,434, Issued November 23, 2004.		X	

FUNDING

Jim Haslett was the first Industry Chair funded by iCORE. For this year he has received funds from NSERC (~$254K), CMC ($311K) as well as cash and in-kind contributions from the University of Calgary (~$500K). His $200K iCORE funds are matched ($200K cash and in-kind) by his industrial partner TRLabs.

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

C. D. Holdenried, J. Haslett and M. Lynch, "Analysis and Design of HBT Cherry-Hooper Amplifiers with Emitter Follower Feedback for Optical Communications", *IEEE Journal of Solid State Circuits*, Vol. 39, No.11, November 2004, pp.1959-1967.

S. Magierowski and S. Zukotynski, "CMOS LC-Oscillator Phase Noise Analysis Using Nonlinear Models," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 51, April 2004, pp. 664-677.

C. D. Holdenried, J.W. Haslett and B. Davies, " A Fully Integrated 10 GB/s Tapped Delay Hilbert Transformer for Optical Single Sideband", *IEEE Microwave and Wireless Component Letters*, in press.*

J. Kulyk, and J.W. Haslett, "A Monolithic CMOS 2368+/-30 MHz Transformer Based Q-Enhanced Series-C Coupled Resonator Bandpass Filter", *IEEE Journal of Solid State Circuits*, accepted for publication March 17, 2005.*

H. Pekau and J. W. Haslett, "A 2.4 GHz Sub-Sampling Mixer with Integrated Filtering", *IEEE Journal of Solid State Circuits*, accepted for publication with revisions, March 31, 2005.*

* It should be noted that each of these publications involves the design, simulation, layout, fabrication and testing of a state-of-the-art RF Integrated Circuit chip. Each design represents approximately 18 months to 2 years of research work by one or more researchers in the group, supported by a large suite of software design tools and hardware testing systems.

REFEREED CONFERENCE PROCEEDINGS (PUBLISHED DURING THE REPORTING PERIOD)

A. Youssef and J. W. Haslett,"Guidelines for the Noise Optimization of 0.18µm CMOS Tuned LNA's", *Proceedings of the 47th IEEE International Midwest Symposium on Circuits and Systems*, Hiroshima, Japan, July 2004, Vol. 3, pp. 9-12.

C. D. Holdenried and J. Haslett, "A DC-6 GHz, 50 dB Dynamic Range, SiGe HBT True Logarithmic Amplifier", *Proceedings of the 2004 IEEE International Symposium on Circuits and Systems*, Vancouver, Canada, May 23-26, 2004, pp. IV289-IV294.

H. Pekau, J. Nakaska, J. Kulyk, G. McGibney, J. W. Haslett and J. McRory, "SOC Design of an IF Subsampling Terminal for a Gigabit Wireless LAN with Asymmetric Equalization", *Proceedings of the Fourth IEEE International Workshop on System-on-Chip* (IWSOC'04), Banff, Alberta, July 2004, pp. 307-313.

K. Townsend and J. Haslett, "A Low-Power 900 MHz Relaxation Voltage Controlled Oscillator in 0.18 um CMOS", *Proceedings of the 16th International Conference on Wireless Communications*, Calgary, Alberta, July 12-14, 2004, pp. 132-136.

V. Devabhaktuni and J.W. Haslett, "Introduction to Theory and Applications of Self Organizing Wireless Sensor Networks", *Proceedings of the 16th International Conference on Wireless Communications,* Calgary, Alberta, July 12-14, 2004, pp. 74-78.

Z. Chen, S. Magierowski, K. Iniewski and J. Haslett, "A Low Voltage RF LC VCO With High PSRR", *Proceedings of the 16th International Conference on Wireless Communications*, Calgary, Alberta, July 12-14, 2004, pp.137-142.

H. Yan, S. Hum, A. Chamseddine, J. Haslett and M. Okoniewski, "Tunable RF Circuits Using Switches and Sectioned Transmission Lines", *Proceedings of the 16th International Conference on Wireless Communications*, Calgary, Alberta, July 12-14, 2004, pp.143-148.

J. Nakaska and J.W. Haslett, "A Novel 10 GHz Inductorless Injection Locked Prescaler IC", *Proceedings of the 16th International Conference on Wireless Communications*, Calgary, Alberta, July 12-14, 2004, pp. 296-301.

J. Nakaska and J. W. Haslett, "An Integrated Inductorless Quadrature Voltage Controlled Oscillator Design In a 47 GHz SiGe Process", *Proceedings of The Northeast Workshop on Circuits and Systems* (NEWCAS 2004), Montreal, Quebec, June 2004, Paper # NC04_166.

K. Iniewski, M. Syrzycki, S. Magierowski, "Reconfigurable 2.5 GHz Phase-Locked Loop for System On the Chip Applications," *Proceedings of the 4th IEEE International Workshop on System-on-Chip for Real-Time Applications*, July 2004, pp. 314 – 317.

Z. Chen, S. Magierowski, K. Iniewski, J.W. Haslett, "A Low Voltage RF LC VCO with High PSRR," *Proceedings of the 16th International Conference on Wireless Communications*, Wireless 2004, July 2004, pp. 137-142 Vol. 1.

K. Iniewski, S. Magierowski, and M. Syrzycki, "Phase Locked Loop Gain Shaping for Gigahertz Operation," *Proceedings of the 2004 International Symposium on Circuits and Systems*, May 2004, pp. 157-160 Vol.4.

S. Magierowski, K. Iniewski, and S. Zukotynski, "A Wideband LC-VCO with Enhanced PSRR for SoC Applications," *Proceedings of the 2004 International Symposium on Circuits and Systems*, May 2004, pp. 173-176 Vol.1.

S. Magierowski, K. Iniewski, S. Zukotynski, "Reducing MOS Varactor Sensitivity to Supply Noise," *Proceedings of the IEEE Workshop on Wireless Circuits and Systems*, May 2004, pp. 27-28.

CONFERENCE PAPERS ACCEPTED FOR PRESENTATION DURING THE REPORTING PERIOD:

K.A. Townsend, K. Iniewski, J.W. Haslett, "Design and Optimization of Low-Voltage Low-Power Quasi-Floating Gate Digital Circuits", accepted for presentation at the 5th IEEE Int. Workshop on System-on-Chip for Real-Time Applications, July 2005, Banff, Alberta.

K. Townsend, J. Haslett, T. K. K. Tsang, M. N. El-Gamal, and K.Iniewski, "Recent Advances and Future Trends in Low Power Wireless Systems for Medical Applications", Accepted for presentation at the *5th IEEE International Workshop on System-on-Chip for Real-Time Applications*, Banff, July 2005.

T. K. K. Tsang, M. N. El-Gamal, K. Iniewski, K. Townsend, and J. Haslett, "Current Status and Trends of CMOS Low Voltage Low Power Wireless IC Designs", accepted for presentation at the 3rd International IEEE Northeast Workshop on Circuits and Systems (NEWCAS), Quebec City, June 2005.

H. Pekau, J.W. Haslett and L. Hartley, "A Re-Configurable High-Speed CMOS Track And Latch Comparator With Rail-To-Rail Input For If Digitization", Accepted for oral presentation at the *2005 IEEE International Symposium on Circuits and Systems*, Kobe Japan, May 2005.

R. H. Johnston and J.W. Haslett, "Antennas for RF Mote Applications", accepted for oral presentation at the *2005 IEEE AP-S International Symposium on Antennas and Propagation*, Washington DC, July 2005.

H. Pekau and J.W. Haslett, "A Comparison of Analog Front End Architectures for Digital Receivers", accepted Jan. 18, 2005 for publication/presentation at the *Canadian Conference on Electrical and Computer Engineering* to be held in Saskatoon, Sask, May 1-4, 2005 (5 pages).

H. Pekau and J.W. Haslett, "Optimization of CMOS switches for RF and IF sampling applications", accepted for presentation at the *17th Annual International Conference on Wireless Communications*, Calgary, July 2005.

Joshua K. Nakaska and James W. Haslett, "A Quality Factor Enhanced Parallel Resonant LC-Tank with Independent Q and Frequency Tuning for RF Integrated Filters," Accepted for presentation at the *5th IEEE International Workshop on System-on-Chip for Real-Time Applications*, Banff, July 2005.

Joshua K. Nakaska and James W. Haslett, "Coarse Tail Current Tuning of Bipolar Voltage-Controlled Oscillators," Accepted for presentation at the *17th Annual International Conference on Wireless Communications*, Calgary, July 2005.

K. Iniewski, V. Axelrad, A. Shibkov, A. Balasinski, S. Magierowski, R. Dlugosz, A. Dabrowski, "3.125 Gb/s Power Efficient Line Driver with 2-Level Pre-emphasis and 2kV HBM ESD Protection," to be presented at the *IEEE International Symposium on Circuits and Systems*, Kobe, Japan, May 2005.

S. Magierowski, K. Iniewski, C. Siu, "Substrate Noise and Characterization of Effects on LC CMOS VCOs," to be presented at the *IEEE Northeast Workshop on Circuits and Systems*, Quebec, City, June 2005.

H. Chan, and S. Magierowski, "MOS Varactors in RF Parametric Amplifiers," To be presented at the *17th International Conference on Wireless Communications*, Calgary, July 2005.

J.F. Bousquet, V. Ramachandaran, R. Salmond, and S. Magierowski "Front-End Evaluation for a CDMA/SDMA WLAN Basestation Chipset," to be presented at the *17th International Conference on Wireless Communications*, Calgary, July 2005.

AWARD WINNING RESEARCH

J. Kulyk and J.W. Haslett, "Q-enhanced RF Transformer Based RF Active Filters", Poster presentation at the 2004 Texpo competition, part of the 2004 MR&DCAN (Microelectronics Research and Development in Canada) workshop in Ottawa, September 30, 2004. Mr Kulyk, an MSc student under Dr Haslett's supervision, won the $3000 Strategic Microelectronics Council of ITAC Design Award for Industrial Collaboration. This was one of three national awards presented, out of 32 projects from 15 universities.

POSTER PRESENTATIONS

J. K. Nakaska and J. W. Haslett, "Novel Inductorless Quadrature VCO and Injection Locked Divider Architectures," Poster presentation at the 2004 Texpo competition, part of the 2004 MR&DCAN (Microelectronics Research and Development in Canada) workshop in Ottawa, Ottawa, September 30, 2004.

K.A. Townsend, J.W. Haslett, "Ultra Low Power VCO Design for Ad Hoc Networks," Poster presentation at the 2004 Texpo competition, part of the 2004 MR&DCAN (Microelectronics Research and Development in Canada) workshop in Ottawa, Ottawa, September 30, 2004.

K.A. Townsend, J.W. Haslett, "Low Power VCOs for Ad Hoc Networks," ICORE Informatics Summit'04, Banff, Canada, June 7-9, 2004.

J. K. Nakaska and J. W. Haslett, "Radio Frequency Voltage Controlled Oscillators," 2004 iCORE Informatics Summit, Banff, Canada, June 7-9, 2004.

J. K. Nakaska and J. W. Haslett, "Radio Frequency Integrated Circuit Research," Presentation, 1st Annual Faculty of Engineering Graduate Student Research Conference, May 3-4, 2004.

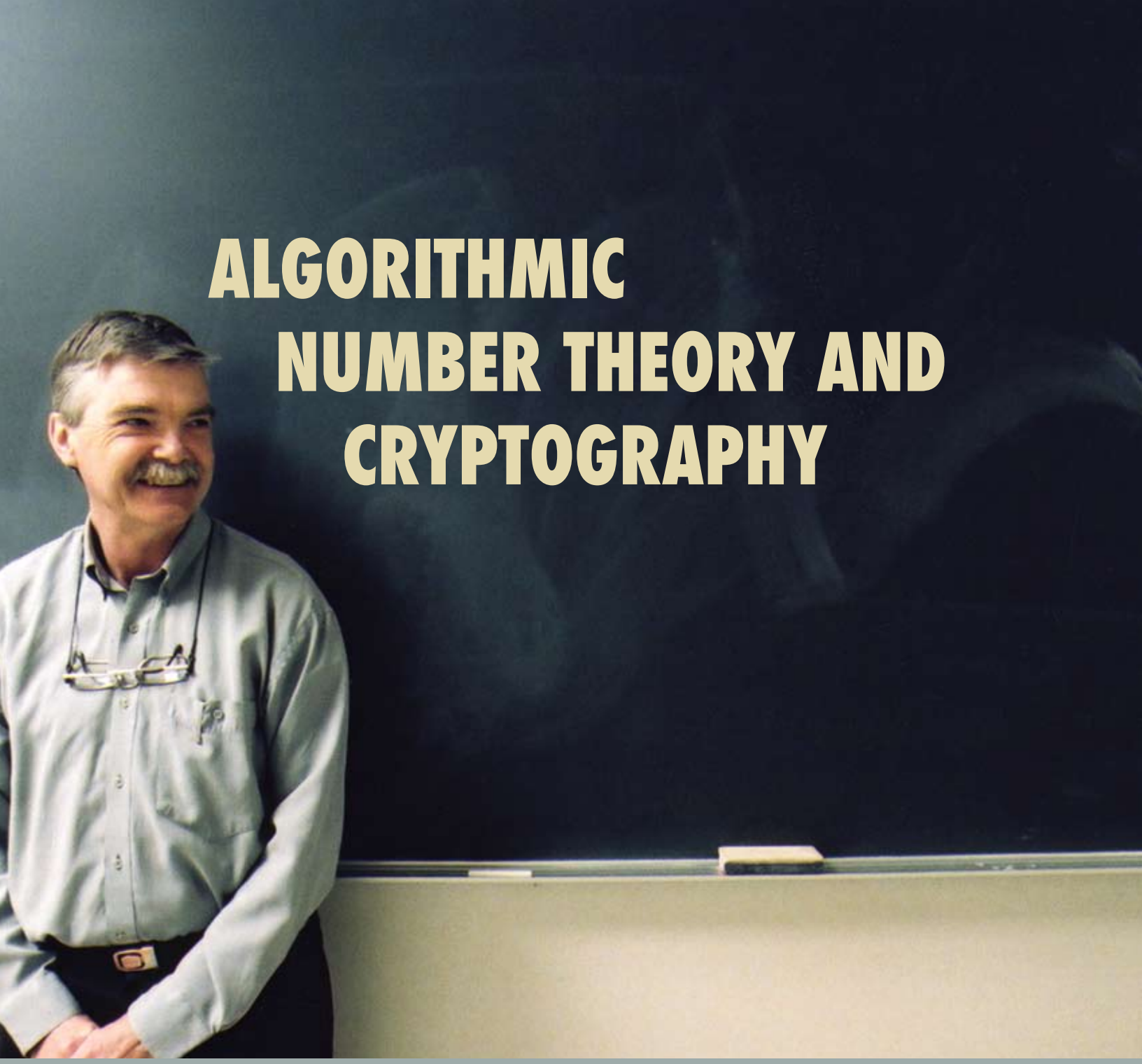
A. Youssef and J.W. Haslett, "Noise optimization of RFCMOS Tuned LNA's",2004 iCORE Informatics Summit, Banff, June 7-9, 2004.

H. Pekau and J.W. Haslett, "Direct RF Digitizing Radio Receivers", 2004 iCORE Informatics Summit, Banff, June 7-9, 2004.

J. Kulyk and J.W. Haslett, "CMOS Intergrated Q-enhanced RF Bandpass Filter." 2004 iCORE Informatics Summit, Banff, June 7-9, 2004.

J. Kulyk and J.W. Haslett, "CMOS Integrated Q-enhanced RF Bandpass Filter." CMC Microelectronics Research and Development in Canada Annual Workshop and Texpo (MR&DCAN), Ottawa, Ontario, Sep. 30, 2004. Strategic Microelectronics Council of ITAC Design Award for Industrial Collaboration (See above).

C.D. Holdenried, J.W. Haslett, and B. Davies, "A Fully Integrated 10 Gb/s Hilbert Transformer," CMC Microelectronics Research and Development in Canada Annual Workshop and Texpo (MR&DCAN), Ottawa, Ontario, Sep. 30, 2004.



ALGORITHMIC NUMBER THEORY AND CRYPTOGRAPHY

The concentrated effort to keep pace with real-world demands has resulted in growing recognition of ICANTC, and thus the University of Calgary, as a centre of excellence for education, research, training and industrial cooperation on information security issues in Canada.

HUGH WILLIAMS

iCORE Chair
Mathematics and Statistics, University of Calgary
http://www.cisac.math.ucalgary.ca/

ICANTC, the iCORE Chair in Algorithmic Number Theory and Cryptography, is dedicated to research and training excellence in cryptology and computer security. Originally mandated to conduct research in fundamental algorithmic number theory and mathematical cryptography, ICANTC expanded its scope in 2004, through the Centre for Information Security and Cryptography (CISaC), to include applied research into the protection of information in every facet of daily life. ICANTC's vision is to be distinguished internationally for our fundamental cryptography research, our exceptional trainees, and our ability to transform knowledge into information assurance and security applications. Today ICANTC, through CISaC, maintains a strong membership cluster that includes academics in such disciplines as mathematics, physics, computer science engineering, history and law, as well as professionals from the public and private sectors

EXECUTIVE SUMMARY

ICANTC's successes over the past year reflect a growing awareness by the public, and in Canadian organizations, of the need for effective and efficient security technologies, methods and policies. These successes include driving information security initiatives that are growing the capacity and commercialization opportunities of Alberta industry as well as information dissemination and training opportunities of immediate relevance to Albertans and Canadians. Some of the exceptional highlights of the year, team achievements, and identified opportunities for the future are presented below.

Achievement Highlights

2004-2005 was a seminal year for ICANTC and reflected the Chair's maturation into the purview of applied information security, including related outreach, training and teaching. The following highlight key achievements:

- Breakthroughs in the design of fast arithmetic of global quadratic fields, leading to very efficient cryptographic schemes based on quadratic number fields as well as elliptic and hyperelliptic curves
- Initiating project Novel Implementation of Cryptographic Algorithms on Custom Hardware Platforms, with the team of iCORE Chair Graham Jullien and industrial partners NE2 and Silicon Graphics, and funded by an NSERC Strategic Grant. This project uniquely combines the ICANTC team's expertise in cryptography with the hardware design and implementation skills of Dr Jullien's ATIPS Lab, and is expected to lead to technology transfer to our industrial partners.
- The development of a promotional piece on Quantum Information and Cryptography – a combination of disciplines that was formally recognized as one of the University of Calgary's "pillars" in its Academic Plan – to document and help University of Calgary's President to position the pillar
- The privacy conference Making Privacy Work, which focused on the western Canadian experience and dissemination of practical knowledge for privacy practitioners. This conference, which attracted over 40 participants from across Canada, helped raise ICANTC's and CISaC's national profile. Its success led to the second, now annual, privacy conference Privacy: Are People Ready to Fight Back?, held on April 21, 2005.
- ICANTC researchers have driven the establishment of an area of concentration in Information Security, a grouping of courses forming part of the Bachelor of Science in Computer Science program. This concentration commences in the fall of 2006.

- The approval and commencement of five new graduate courses in Number Theory and Cryptography. In addition, new parallel graduate components for two senior level undergraduate courses in Cryptography were created.
- Active research and knowledge dissemination efforts have resulted in the publication or submission for publication of nearly 50 articles, and over 50 lectures both at home and around the world
- The development of effective collaborations with:

  Professional associations, such as the Calgary chapter of SPIE, the Security Professionals Information Exchange

  Academia, such as the University of Calgary's Centre for Military and Strategic Studies, the Technical University of Darmstadt (Germany), and the Mathematical Institute of the Polish Academy of Sciences

  Small and medium businesses both locally and nationally, such as NE2 Corporation and Big BangWidth, as well as large companies such as General Dynamics Canada
- Brought over 20 renowned researchers to the U of C as part of our Distinguished Visitors program
- Graduated seven Master's and two PhD students and recruited new exceptional talent in the form of two new postdoctoral fellows, ten new graduate students who started in 2005, three new visiting PhD students (from the University of Illinois, supervised by ICANTC researchers under our partnership agreement with that institution), and six new graduate students commencing in the fall of 2006.
- Appointed a Technical Advisory Panel for CISaC and increased CISaC membership to 27 and CISaC's Management Board to six (two new members from industry joined the Board).
- In January 2005 Michael Jacobson and Hugh Williams, representing CISaC, in conjunction with the Centre for Military and Strategic Studies and the Department of Computer Science at the University of Calgary, launched a series of lectures devoted to various aspects of information protection and related issues. Since January 2005, the series has enjoyed considerable success, routinely attracting 50 to 60 attendees from business and academia who represent many aspects of the large spectrum of topics involving information security.
- A BIRS Workshop on Explicit Methods in Number Theory took place November 13-18, 2004, immediately followed by a second BIRS weekend workshop. A third workshop will take place November 5-10, 2005.
- Together with Deakin University in Melbourne, Australia, we participated in holding a workshop on Polynomial Aspects of Cryptography, July 7-12, 2004. The conference brought together 30 experts across the fields of algebra, cryptography and algorithm implementation in an Oberwolfach-style meeting.
- Renate Scheidler taught a summer course Cryptology at the third annual Atlantic Association for Research in the Mathematical Sciences (AARMS) Summer School held at Memorial University of Newfoundland, St. John's, Newfoundland, from July 12 - August 6, 2004. There were 30 graduate students from nine different countries, including Canada, the US, Turkey, and various European countries.

Hugh Williams with Mike Jacobson and Renate Scheidler

Team Achievements

Our research team thrived in 2004-2005, with the publication or submission for publication of almost 50 research articles and over 50 presentations locally and all around the world. ICANTC researchers were principal investigators on personal research grants totaling over $730K annually, and were co-investigators on projects for which funding exceeded $960K. Over the past year, our team organized or co-organized eight conferences, workshops, and panels, and successfully graduated nine MSc and PhD students, several of whom have begun careers with Alberta

companies or continued on to do graduate work with our group.

New Opportunities

The ICANTC Chair through CISaC is teaming up with the Institute for Quantum Information Science (IQIS) and the Advanced Technology Information Processing Systems (ATIPS) teams to establish the Calgary Laboratory for Information Assurance and Security (CLIAS).

The year 2004-2005 was a decisive and productive one for ICANTC, as it reflected the organization's maturation beyond theoretical cryptography into the broader purview of applied information security, including outreach, training, and teaching. The concentrated effort to keep pace with real-world demands has resulted in growing recognition of ICANTC, and thus the University of Calgary, as a centre of excellence for education, research, training and industrial cooperation on information security issues in Canada.

While ICANTC's original mandate focused on conducting research in algorithmic number theory and cryptography, in the four years since its inception it has become evident that its objectives have grown beyond this vision. The Centre for Information Security and Cryptography (CISaC), operating under the aegis of ICANTC, is the vehicle by which the iCORE chair can conduct these expanded activities in the area of information security, effecting academic and industrial collaborations and training in addition to research.

CISaC-Related Activities

CISaC is a multi-disciplinary research institute that operates as a collaborative faculty-based centre supported and administered by the Faculty of Science at the University of Calgary. CISaC brings together researchers, students and professionals with a wide variety of expertise to work in partnership on projects involving information security. Presently the iCORE chair is CISaC's main funder, although our goal is for the Centre to have a life of its own beyond that of ICANTC.

The Centre's program today offers research, outreach, training and teaching in information security and cryptography as well as emerging issues such as the ethical and legal ramifications. Partnerships with professionals working in the information security industry are allowing us to develop opportunities for collaborative training and course development, all with a goal of providing students with the kind of education that will allow them to find employment in the burgeoning field of information security.

Since last year, CISaC has acquired seven new members for a total of 27. We continue to constantly expand CISaC through activities such as forming effective collaborations with organizations such as the Security Professionals Information Exchange (SPIE), maintaining an active Distinguished Visitors' Program to bring top researchers to the University of Calgary, and recruiting top students at all levels – undergraduate, masters, PhD and post-doctorate – to be part of our program.

As mentioned before, CISaC is also working to offer a sequence of undergraduate courses as part of an area of concentration in Cryptography, developing courses for a concentration in information security, and offering graduate courses in cryptography that can be accessed by students in mathematics, computer science and engineering.

The continuing development of CISaC as an important means of stimulating interaction between the iCORE chair and the outside community is now providing opportunities for future exploitation.

Recently, the CISaC management board established a Technical Advisory Panel (TAP). The TAP is a group of 12 internationally recognized experts, representing various aspects of the extensive area of information security. This panel will provide expertise that CISaC can draw upon for advice.

Other ICANTC Research Activities:

- Dr Williams is one of the principal investigators associated with the Advanced Microsystems Integration Facility (AMIF) initiative in support of research associated with the Medical Ward of the 21st Century. This has already received $500,000 in funding from the University of Calgary over the next three years. The proposed facility will enable the development and integration of novel microsystems devices in support of wireless patient vital sign monitoring and patient location within the new Ward of the 21st Century. This facility, located at Foothills Hospital in Calgary, will incorporate sophisticated biomedical sensors and a range of RF stationary and mobile devices that all connect to wireless, ad hoc, self-organizing networks. Dr Williams will be providing the expertise needed to assure secure transmission of the medical data through the wireless channels.

- Dr Williams is also a member of a research team headed by Professor Jim Haslett, which is applying for a $1,136,500 NSERC Strategic Grant for the project Design of Next Generation Integrated Wireless Medical Devices for Patient Vital Sign

Monitoring. The protection of medical records and data is key to patient privacy as doctor-patient confidentiality takes on new meaning in our electronic age. Colleagues at CISaC are currently working on the implementation of a novel crypto protocol. The research group will incorporate secure data transmission into the proposed system to transmit encoded data securely in the wireless environment. (The security work is part of a three-year strategic grant and will converge in year three of this proposal). The challenge is to develop protocols that can be implemented in hardware at very low power levels, while at the same time providing a sufficient level of security.

- Dr Williams is the principal research investigator for the Security and Emerging Applications Laboratories (SEALs, formerly RETSBAR) project. The University of Calgary is proposing to work with industrial partners BigBangwidth, Legato/EMC, and Persist/HP to enhance the speed of innovation of scientific research through advanced network and security concepts within the university. The purpose of this project is to provide industrial participants and researchers high-bandwidth access to remote storage to enable secure and encrypted real-time backup and restore of sensitive computing applications. The commercial impact potential of this project is tremendous for creating local spin-off companies that will employ graduates from the University of Calgary and other provincial universities and schools of higher education. Demand for a highly skilled workforce with data transmission security knowledge, business continuity, optical networks and data backup and recovery experience will be strong. This is a $2,800,000 project, and there has been a lot of interest in funding a large part of it from Western Economic Diversification Canada (WD).

RESEARCH PROJECTS

As indicated by the title of the Chair, the research conducted by the ICANTC team centers around computational and algorithmic number theory as well as theoretical and applied cryptography. Our work in cryptology includes the design, analysis, testing, implementation, and benchmarking of cryptographic schemes, with applications to information and network security. Our number theoretic research focuses on the development of fast arithmetic and the computation of invariants and other related structures for certain algebraic constructs called global fields, such as algebraic number fields and function fields. The latter includes the celebrated elliptic curves that are used in commercial cryptographic applications.

Our number theoretic and cryptographic research is closely connected. The security of the cryptographic protocols that we study is generally based on a class of underlying very difficult mathematical problems summarized under the name discrete logarithm problem (DLP). The methods for solving various versions of the DLP and thus breaking the cryptographic protocols in question are frequently extensions of the algorithms used for computing invariants of global fields. Thus, in order to accurately assess the security of these cryptosystems, it is vital to study and understand the algorithms for determining invariants. In addition, fast arithmetic in global function fields leads to a higher level of efficiency of these mathematically based cryptosystems, which is critical in the context of commercial applications.

Quadratic Number Fields

Quadratic fields represent a very active area of number theoretic research as well as a suitable setting for cryptography. We have made considerable progress in a number of arithmetic and algorithmic problems for which we now hold the fastest unconditional verification procedures known. Furthermore, we were able to exhibit new infinite families of quadratic fields for which a certain invariant called the fundamental unit (which is generally extremely large) is unusually small and can be explicitly determined. These families are used in the NICE cryptosystem described below and are therefore of number theoretic, as well as cryptographic, significance.

Elliptic and Hyperelliptic Curves

These are the function field cousins of quadratic number fields and are the subject of intense study, mainly because they serve as the basis for extremely efficient and secure cryptographic protocols, including the commercially used elliptic curve systems. We have recently shown that the so-called real model of a hyperelliptic curve allows for even faster cryptographic key exchange than the conventional (imaginary) model, and are in the process of applying a very fast ideal reduction procedure called NUCOMP to this setting. We also continue our investigation of the hyperelliptic DLP as well as applications of the Weil pairing for elliptic curves to identity-based cryptography. Another strictly number theoretic project involving hyperelliptic fields is the construction of such fields with unusually large 3-rank; this also has some interesting connections to our work on cubic fields described below.

Global Cubic Fields

Cubic fields are the next step after quadratic fields in the hierarchy of global fields. While they are less well

understood than their quadratic counterparts, recent results have shown that certain special types of these structures, such as the so-called Picard Curves, can be used for cryptographic schemes that are essentially as efficient and secure as hyperelliptic curve systems. Our study of the structure and arithmetic of cubic fields is a long-term research initiative that includes several ICANTC associated researchers and graduate students as well as teams of undergraduate research assistants hired every summer to design and implement computer code for our algorithms.

Sieving Devices and Primality

A number sieve is a special-purpose hardware device that performs certain types of number theoretic computations extremely efficiently. The construction of CASSIE, the latest and fastest in a long line of such sieves built under Hugh Williams' supervision, was recently completed. CASSIE has been used to provide numerical data to assist in solving certain number theoretic problems, including searching for so-called pseudosquares which turn out to have interesting applications to the generation of cryptographic signatures. Digital signatures, used in e-commerce and online transactions, allow communicating parties to authenticate their identities, and the so-called Rabin-Williams signatures are particularly efficient. Their verification process requires the generation of a 100-bit prime, which can now be done very quickly thanks to CASSIE and our new pseudosquare search method. We have recently discovered how to extend the use of pseudosquares in primality testing to pseudocubes and even to pseudo r-th powers in general.

Applied Cryptography and Network Security

With the help of two of our graduate students, we are currently in the process of working with our industrial partner NE2 to establish a set of efficiency criteria for cryptographic key establishment algorithms and compare a number of these methods, including NE2's technique, under these criteria. In joint work with several of our colleagues in Computer Science, including iCORE Professor and Industrial Chair Dr C. Williamson, we have also devised mechanisms for making computer networks more secure, such as a practical and more secure version of the buses anonymity protocol as well as a novel port knocking scheme to allow only authorized users to gain access to a firewall protected network.

OBJECTIVES FOR NEXT YEAR

The CLIAS Initiative (www.clias.ca)

In line with our vision, our main objective is the establishment of the Calgary Laboratory for Information Assurance and Security (CLIAS). This venture is a team effort by the ICANTC Chair (through CISaC), the Institute for Quantum Information Science (IQIS), led by iCORE Professor Barry Sanders, and the Advanced Technology Information Processing Systems (ATIPS) Lab, led by iCORE Chair Graham Jullien, and is being assisted by industrial partners General Dynamics Canada and NE2 Corporation.

Hugh Williams and some research team members at the 2005 Banff Informatics Summit

Information security in the electronic age is a major concern for Canadians. Nationwide, the problems of information assurance and security are not adequately addressed. Although IAS legislation is in place, Canada lacks the infrastructure necessary for its consistent widespread implementation. This gap in capability is an opportunity for the province of Alberta to fill this immediate need and establish a national world-class institute for IAS. CLIAS will be built upon the following internationally recognized University of Calgary institutions:

- ATIPS: provides excellence in cryptographic hardware implementations.
- CISaC: represents leadership in fundamental and applied cryptography and security solutions.
- IQIS: leads in the understanding, development and testing of quantum algorithms and quantum cryptography.

CLIAS represents a high-tech business opportunity for Alberta that will be a cornerstone for information security in Canada.

Other objectives for our team include:

- Holding the second conference devoted to privacy, entitled Privacy: Are People Ready to Fight Back?. Topics will include identity theft, privacy and HR policies and practices, phishing, the U.S. Patriot Act and the impact on Canadian privacy, electronic health registry, and tools for protecting privacy. Speakers will come from across Canada, and represent academia, government and industry. We are planning a third annual privacy meeting for the spring of 2006.
- Coordinating and preparing for The Fields Institute Thematic Program in Cryptography, which will take place in Fall 2006. The program will include a series of one-week workshops, graduate courses and distinguished lecturers. This event will bring together researchers from areas that seldom have the opportunity to interact in an atmosphere where problems at the intersections can be explored. The aim is to overcome these obstacles and foster new links between both areas.
- Working with Martin Kirk (Director of Research Services, U of C), Brian Moore (BigBangwidth) and the Dean of the Faculty of Science to develop a business plan for SEALs in order to secure funding
- Expanding information security outreach and training and enhance our profile by sponsoring and providing activities such as information sharing, public lectures, special workshops, conferences and summer schools. This includes our Distinguished Security Lecture Series, which will resume in the fall of 2005, and our new partnership agreement with Calgary's Security Professionals Information Exchange (SPIE) chapter. Another example is the Summer School on Computational NumberTheory and Applications to Cryptography, which will take place June 19-July 7, 2006.
- Continuing to nurture and develop more partnerships between other academic institutions and industrial companies like the Wyoming Institute for Discrete Mathematics and Information Assurance (WIDMIA), BigBangwidth, NE2 Corporation, Silicon Graphics and General Dynamics Canada.
- Building on last year's success and continue to recruit more undergraduate, graduate and post-doctoral students.
- Continuing to raise our research profile by inviting outstanding visitors through our Distinguished Visitors Program.
- One of the fundamental issues in cryptography is determining the computational complexity of the underlying mathematical problems that modern public-key cryptosystems are based on. Mark Bauer is looking at the question of how difficult is the elliptic curve discrete logarithm and whether there any other problems that we could show of the same complexity. Safuat Hamdy and Bauer proved some limited results on the connection between elliptic curve discrete logarithms and the analogous problem in number fields.
- Mark Bauer and Renate Scheidler are continuing their work on examining general cubic function fields, developing the foundations for the arithmetic in the Jacobian of certain curves that correspond to cubic function fields of a special form. The end goal of this project is to develop algorithms that are suitable for arbitrary cubic function fields.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

NAME	ROLE, TOPIC, AWARDS AND OTHER INFO
Dr Hugh Williams	Professor, Department of Mathematics & Statistics iCORE Chair in Algorithmic Number Theory & Cryptography CISaC Director
	Successfully applied to the Fields Institute for support of a six-month program devoted to cryptography; budget is $325K. NSERC Discovery Grant $30K pa, 2005-2009 MITACS Award $135K pa, 2005-2007. This award is shared with Alfred Menezes at the CACR in the University of Waterloo. It also includes $15K to be used for industrial internships for graduate students. Alberta iCORE, iCORE Chair Establishment Award, $600K pa, 2001-2006 NSERC, Research Grant, $150K, 2000-2005 Special Session Organizer, Computational Number Theory, Canadian Number Theory Association meeting, held June 20-25, 2004 Had the title Professor Emeritus bestowed on him at the 125th Annual Convocation at the University of Manitoba, on May 27, 2004 H.C. Williams and R. Scheidler, Co-Investigators, Novel Implementation of Cryptographic Algorithms on Custom Hardware Platforms, NSERC Strategic Projects Research Grant; total award: $506K (2004-2006) Member, Organization Committee, MITACS Cyber Security Workshop, held in Ottawa, November 29-30, 2004 Member, Program Committee for Asiacrypt 2005; to be held in Chennai, India, December 2005 Special Session Organizer and attendee, Computational Number Theory Association VIII Meeting, June 20-25, 2004, Fields Institute, University of Toronto Attended the Algorithmic Number Theory Symposium, June 12-18, 2004, University of Vermont

Faculty Team Members

NAME	ROLE, TOPIC, AWARDS AND OTHER INFO
Dr Mark Bauer	Assistant Professor, Department of Mathematics and Statistics
	NSERC Discovery Grant - $13K pa, 2004-2007 Lecturer and student mentor at the graduate student summer IMA summer school on cryptography and coding theory, Notre Dame University, June 19-27, 2004 Host/Organizer, research seminar in Discrete Mathematics 2004-2005
Dr Michael J. Jacobson, Jr.	Assistant Professor, Department of Computer Science Member, CISaC Management Board
	CFI Infrastructure Operating Fund - $73,313 over four years. This award is to pay operating expenses related to the CFI-funded Advanced Cryptography Laboratory not budgeted in the original application. It will be used to pay part of our technician's salary (Marc Wrubleski) NSERC Discovery Grant; $15K pa; 2001-2004 University of Calgary Start-up Grant; $30K; 2002-2004 University Research Grants Committee (URGC) starter grant - $9989; April 1, 2004-September 30, 2005; project title: Computing discrete logarithms in hyperelliptic curves Lecturer and student mentor at the graduate student summer IMA summer school on cryptography and coding theory, Notre Dame University, June 19-27, 2004

NAME AND POSITION	ROLE, TOPIC, AWARDS AND OTHER INFO
Dr Richard Mollin	Professor, Department of Mathematics & Statistics
	NSERC Research Grant; $16K pa; 2001-2005 Awarded his fifth Killam award, this one for the writing of the CODES book. This will free him from duties for the Winter 2005 term to complete the project
Dr Renate Scheidler	Associate Professor, Department of Mathematics & Statistics and the Department of Computer Science iCORE Research Associate Member, CISaC Management Board
	University of Calgary URGC Research Grant for the project entitled Efficient Arithmetic in Global Quadratic Fields, $9,986. March 2003 to November 30, 2005 NSERC Research Grant, $17K pa, 2002-2005 H.C. Williams and R. Scheidler, Co-Investigators, Novel Implementation of Cryptographic Algorithms on Custom Hardware Platforms, NSERC Strategic Projects Research Grant; total award: $506K (2004-2006). Member of the Programming Committee of Algorithmic Number Theory Symposium ANTS VI, June 13-18, 2004, United States Naval Academy, Annapolis (Maryland, USA) Member of the Dean of Science's Committee for the Re-Investment in Science (CRIS) Member of the organizing committee for a thematic semester in cryptography that will take place at the Fields Institute in Toronto in the fall of 2006. Hugh Williams is the chief organizer of this six-month program devoted to cryptography

Affiliated Faculty

NAME AND POSITION	ROLE, TOPIC, AWARDS AND OTHER INFO
Dr Vassil Dimitrov	Associate Professor, Department of Electrical & Computer Engineering Member, CISaC Management Board Member
	NSERC Research Grant; $26K pa, 2001-2005 Principal Investigator, NSERC Strategic Grant Novel Implementation of Cryptographic Algorithms on Custom Hardware Platforms, $506K, 2004-2006
Dr Graham Jullien	Professor, Department of Electrical & Computer Engineering
	NSERC Research Grant, $400K, 2002-2007

Postdoctoral Fellows

NAME AND POSITION	ROLE, TOPIC, AWARDS AND OTHER INFO
Dr Stéphane Lemieux	Began May 1, 2004
Dr Bodo Möller	Began January 1, 2005
Dr Pradeep Mishra	Began December 15, 2004
Dr Roger Patterson	Began May 1, 2004

PhD Students

NAME AND POSITION	ROLE, TOPIC, AWARDS AND OTHER INFO
Andreas Hirt	PhD, Computer Science
	NSERC CGS-D2, $35K per year, 2004 - 2006 iCORE Studentship, $10K per year, 2004 - 2006 and $15K per year, 2006 - 2009 Dean's Research Excellence Award, $3K per yer, 2004 and 2005 Alberta Ingenuity Studentship, $22K* per year + $1.5K per year research allowance, 2004 - 2009 (reduced to $7K per year + $1.5K reserach allowance while NSERC CGS-D2 is held)
Eric Roettger	PhD, Mathematics
Pieter Rozenhart	PhD, Mathematics
Reg Sawilla	PhD, Computer Science
	NSERC PGS-D award was changed to an NSERC CGS-D at $35K per year, 2004 - 2006 Graduate Student Scholarship, $10K per year, 2004 - 2006 Alberta Ingenuity Incentive Award, $7K per year + $1.5K per year research award, 2004-2006
Adrian Tang	PhD, Mathematics
Kjell Wooding	PhD, Mathematics and Electrical and Computer Engineering
	NSERC PGS-D, $21K per year, 2004-2006 Alberta Ingenuity Studentship, $22K* per year + $1.5K per year research allowance, 2004 - 2009 (reduced to $7K per year + $1.5 reserach allowance while NSERC CGS-D is held)

MSc Students

NAME AND POSITION	ROLE, TOPIC, AWARDS AND OTHER INFO
Andy Chan	MSc, Computer Science
	CPSC Departmental research award, $6K, 2004-2005
James Chou	MSc, Mathematics
Rennie de Graaf	MSc, Computer Science
Chris Foster	MSc, Mathematics
	Defense is expected in May 2005
Guarav Jain	MSc, Computer Science
Shantha Ramachandran	MSc, Computer Science
	NSERC PGM $17.5K 2004 - 2006 iCORE $12K 2004 - August 2006 University of Calgary entrance award, $3K, 2004
Alan Silvester	MSc Mathematics
Nick Sullivan	MSc Mathematics

Visiting PhD Students

NAME AND POSITION	ROLE, TOPIC, AWARDS AND OTHER INFO
Eric Landquist	PhD student, University of Illinois at Urbana-Champaign (USA) January-June 2005
Jonathan Webster	PhD student, University of Illinois at Urbana-Champaign (USA) January-June 2005
Qingquang Wu	PhD student, University of Illinois at Urbana-Champaign (USA) February-July 2005

Summer Students 2004

NAME AND POSITION	ROLE, TOPIC, AWARDS AND OTHER INFO
Anguo Dong	Supported by Renate Scheidler's NSERC grant Part-time May - August 2004; Renate Scheidler has funded and supervised Dong since May 1, 2003
Andy Chan	New MSc student working with Michael Jacobson Full-time May-August 2004
Keith Chung	NSERC scholar working with Michael Jacobson Full-time May-August 2004
Rennie de Graaf	Working with Michael Jacobson; supported by Hugh Williams' iCORE grant Full-time May-August 2004
Diana Nguyen	NSERC scholar, working with Renate Scheidler Full-time May-August 2004
Nick Sullivan	New MSc. Student working with Michael Jacobson and Renate Scheidler Full-time May-August 2004
Mark Velichka	NSERC scholar working with Michael Jacobson and Renate Scheidler Full-time May-August 2004
Hameed Zaman	Working with Mark Bauer and supported by Mark Bauer's NSERC grant and Hugh Williams' iCORE grant Full-time May-August 2004

Support Staff

NAME AND POSITION	ROLE, TOPIC, AWARDS AND OTHER INFO
Susan Schuck	Administrative Support
Marc Wrubleski	Computer Technician
William Lorimer	CISaC Strategic Research Manager Hired in March 2005 Responsible for developing and maintaining connections between ICANTC and the corporate sector, and for implementing and maintaining our new IP strategy.

Long Term Visitors

NAME AND POSITION	ROLE, TOPIC, AWARDS AND OTHER INFO
Dr Laurent Imbert	Visiting from CNRS Montpellier (France) until December 2005
Dr Siguna Müller	Visiting from Universität Klagenfurt (Austria) until August 2005

COLLABORATIONS AND AWARDS

INSTITUTION	NATURE OF COLLABORATION
PROVINCIAL	
ATIPS, University of Calgary	Working to engineer a small, wireless device that can be implanted in patients and used to transmit data securely over very short distances. Also joint project Novel Implementation of Cryptographic Algorithms on Custom Hardware Platforms (NSERC Strategic Grant, Principal Investigator: Vassil Dimitrov, member on the CISaC management board).
Security Professionals Information Exchange (SPIE)	Working with SPIE to develop new courses, a possible internment program for master's students, and a shared information program.
Calgary Laboratory for Information Assurance and Security (CLIAS), formerly known as the Centre of Excellence for Applied Information Assurance or CEIAS.	R. Scheidler and H. Williams are working with Professors G. Jullien and B. Sanders and M. Kirk (Director, Research Services) to develop a plan for the establishment of this facility at the University of Calgary. Nationwide, information assurance and security is not adequately addressed. Addressing this key issue is essential for protecting the privacy and security of individuals, organizations, and government.
NATIONAL	
Fields Institute	Received $325K to support a six-month program devoted to cryptography. This includes a series of lectures, graduate courses and distinguished lecturers. http://www.fields.utoronto.ca/programs/scientific/06-07/crypto/
INTERNATIONAL	
Mathematical Institute of the Polish Academy of Sciences.	
Technical University of Darmstadt	
INDUSTRIAL	
BigBangWith, Legato/EMC and Persist/HP	Security and Emerging Applications Laboratories (SEALs, formerly RETSBAR) project; proposing to work with industrial partners to enhance the speed of innovation of scientific research through advanced network and security concepts within the university.
General Dynamics, Calgary	Currently working to develop CIIAS. This should result in a means by which ICANTC can effect technology transfer.
NE2	Currently working to develop CIIAS. Also working on the project entitled Novel implementation of cryptographic algorithms on custom hardware platforMs The principal investigator is Vassil Dmitrov, who is part of the CISaC management board.

INTELLECTUAL PROPERTY

While ICANTC is mainly concerned with the development of scientific ideas, some of our current work is beginning to involve research that might lead to commercial applications. This is certainly true in the case of some of our joint work with ATIPS, and possibly even IQIS. Thus, we have developed a strategy for the protection of the intellectual property that we are now producing. In doing this we have been guided by two principles: flexibility and vigilance.

FUNDING

This year Hugh Williams and his team receive federal funding from several sources such as NSERC (~$382K), CFI (~$143K), MITACS ($255K) and The Fields Institute (~$163K). In addition, the University of Calgary contributed $15K to the $600K provided by his iCORE Chair funding.

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

J.-C. Bajard and L. Imbert, "A Full RNS Implementation of RSA", *IEEE Transactions on Computers*, 53 (6) (2003), pp. 769-774.

M. Bauer, E. Teske and A. Weng, "Point Counting on Picard Curves in Large Characteristic." Accepted in *Mathematics of Computation*, 21 pp.

K. Cheng and H.C. Williams, "Some Results Concerning Certain Periodic Continued Fractions". Accepted in *Acta Arithmetica*, 22 pp.

M. J. Jacobson, R. Scheidler and H.C. Williams, "An Improved Real Quadratic Field Based Key Exchange Procedure". Accepted October 25, 2004 by *Journal of Cryptology*, 30 pp.

R .A. Mollin, "A Note on the Diophantine Equation $D_1x^2+D_2 = ak^n$". To appear in *Acta Mathematica Academiae Paedagogicae Nyíregyháziensis*.

R. A. Mollin, "Class Groups of Quadratic Equations." To appear in *JP Journal of Algebra, Number Theory and Applications*.

R. A. Mollin, "Class Numbers, Quadratics, and Exponential Diophantine Equations." To appear in *JP Journal of Algebra, Number Theory, and Applications*.

R. A. Mollin, "Eisenstein Equations, and Central Norms." To appear in *Math Reports, Acad. Sci. Canada*.

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J.-C. Bajard, L. Imbert and T. Plantard, "Arithmetic Operations in the Polynomial Modular Number System," Research Report LIRMM #04030, September 2004. To appear in the Proceedings of to the *17th IEEE Symposium on Computer Arithmetic (ARITH'17).*

J.-C. Bajard, L. Imbert and G.A. Jullien, "Parallel Montgomery Multiplication in GF(2k) using Trinomial Residue," Arithmetic Cryptology ePrint Archive: Report 2004/279, Research Report LIRMM #04040, October 2004. To appear in the proceedings of the *17th IEEE Symposium on Computer Arithmetic (ARITH'17).*

J.-C. Bajard, L. Imbert, P.-Y. Liardet and Y. Teglia, "Leak Resistant Arithmetic Cryptographic Hardware and Embedded Systems," *CHES 2004,* number 3156 in LNCS, Boston, MA, USA, August 2004, pp.62-75.

J.-C. Bajard, L. Imbert and T. Plantard, "Modular Number Systems: Beyond the Mersenne Family," Selected Areas in Cryptography: 11th International Workshop, SAC 2004, Waterloo, Canada, August 9-10, 2004, volume 3357 in Lecture Notes in *Computer Science, Springer-Verlag 2005*, pp.159-169.

P. Berrizbeitia, S. Müller and H.C. Williams, "Pseudocubes and Primality Testing". Proceedings of the Sixth Algorithmic Number Theory Symposium ANTS-VI, Lecture Notes in *Computer Science,* vol. 3976, pp. 102-116.

V. Berthé and L. Imbert, "On Converting Numbers to the Double-Base Number System", Research report LIRMM #04005, June 2004. To appear in *Advanced Signal Processing Algorithms, Architectures and Implementations, Proceedings of SPIE,* Denver, CO, USA, August 2004.

P. Chan, G. A. Jullien, L. Imbert, V. Dimitrov and G.H. McGibney, "Fault-Tolerant Computations within Complex FIR Filters," *IEEE Workshop on Signal Processing Systems - SIPS 2004,* October 13-15, 2004, Austin, Texas, USA, pp.316-320.

M. J. Jacobson, "The Security of Cryptosystems Based on Class Semigroups of Imaginary Quadratic Non-Maximal Orders," *Proceedings of ACISP 2004*, LNCS 3108, Sydney, Australia, 2004, pp. 149-156.

M. J. Jacobson, A. J. Menezes and A. Stein, "Hyperelliptic Curves and Cryptography", High Primes and Misdemeanors: Lectures in Honour of the 60th Birthday of Hugh Cowie Williams, *Fields Institute Communications*, vol. 41, AMS, 2004, pp. 255-282.

M. J. Jacobson, H. C. Williams, and K. Wooding, "Imaginary Cyclic Quartic Fields with Large Minus Class Numbers", Proceedings of the Sixth Algorithmic Number Theory Symposium ANTS-VI, Lecture Notes in *Computer Science*, vol. 3076, pp. 280-292.

R. Scheidler, "Algorithmic Aspects of Cubic Function Fields". Proceedings of the Sixth Algorithmic Number Theory Symposium ANTS-VI, Lecture Notes in *Computer Science*, vol. 3976, pp. 395-410.

A. Hirt, M.J. Jacobson, Jr., and C. Williamson, "A practical buses protocol for anonymous internet communication", to appear in *PST 2005*.

R. deGraaf, J. Aycock and M.J. Jacobson, "Port Knocking with Strong Authentication". To appear in *ACSAC 2005*.

A. Hirt and J. Aycock., "Anonymous and Malicious". Accepted April 4, 2005 by *Virus Bulletin 2005 Conference.*

BOOKS

R. A. Mollin, "CODES – The Guide to Secrecy from Ancient to Modern Times".

NANOCORE
NANOSCALE ENGINEERING PHYSICS INITIATIVE

Michael Brett
iCORE Professor, Nanocore
iCORE/NSERC/Micralyne Industrial Research Chair
Electrical and Computer Engineering, University of Alberta

Mark Freeman
iCORE Professor, Nanocore
Physics, University of Alberta

MICHAEL BRETT and MARK FREEMAN

http://www.nanocore.ca

The principal mission of Nanocore is to build upon existing strengths in nanoscale engineering physics to develop world-class expertise in selected areas of nanotechnology. Specifically, the areas can be summarized as nanofabrication methods related to thin film technology, and advanced characterization of nonequilibrium physical properties of nanosystems relevant to future ICT. The Industrial Chair Establishment (ICE) program aims to develop device applications of nanoengineered materials, with assistance from industrial partner Micralyne.

EXECUTIVE SUMMARY

The iCORE Nanoscale Engineering Physics Initiative (Nanocore) led by Drs Mark Freeman and Michael Brett has concluded its fourth year of operation, with the related effort in applied nanotechnology research strengthened through the second year of Micralyne/NSERC/iCORE Industrial Research Chair position held by Brett. The Nanocore and ICE programs are continuing to play an instrumental role in the growth of nanoscience and engineering research in Alberta. Nanocore has led the initiative to establish the University of Alberta Micromachining and Nanofabrication Facility (NanoFab), and helped to attract the National Institute for Nanotechnology to Edmonton.This development is accomplished in parallel with the training of a large number of personnel developing at the forefront of nanoscience and engineering. Continued success in recruitment of research trainees has led to an outstanding group of graduate students. Of 19 graduate students directly supervised by Brett or Freeman, 14 have been awarded major scholarships from NSERC, or Alberta Ingenuity. Brett and Freeman continue their leadership in establishment, facilitation and operation of the University of Alberta (NanoFab), having received awards over the past three years (as principal or co-investigators) of infrastructure and operating support exceeding $20M from CFI, NSERC, ASRIP, and Western Diversification. Another measure of Nanocore/ICE success is the ongoing activity in Alberta by former Nanocore/ICE trainees. Over the past two years, seven trainees have taken their skills into the growing local Alberta nanotech industry.

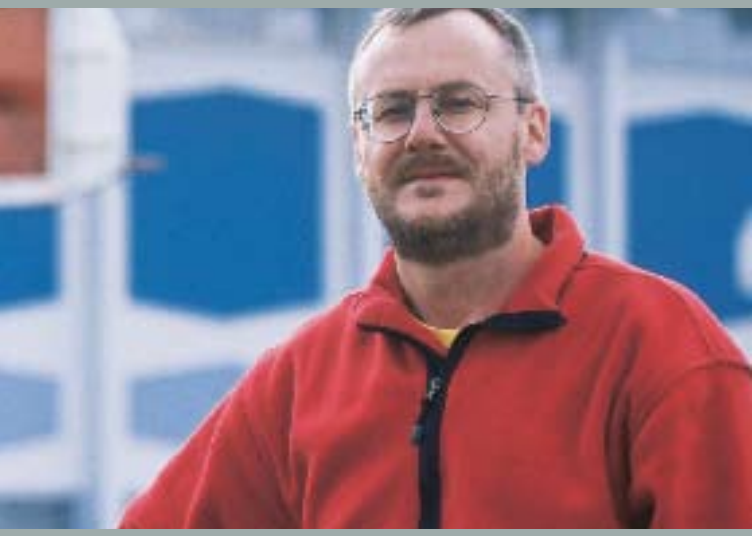
Nanocore/ICE continues to be instrumental to the evolution of Albertan and Canadian capabilities in nanotechnology. Our NanoFab, establishment of which was led by Brett and Freeman, is the best in Canada and competes in its specialties with any in the world. As a result, the NanoFab has attracted users from eight universities and six provinces, and there are already eight new ICT-related spin-off companies in Alberta that rely on the facilities for product development. Over 550 researchers have used the NanoFab equipment. Having this cluster of nanofabrication expertise nearby was an influential factor in selecting the location of the National Institute of Nanotechnology in Edmonton. Nanocore/ICE funding largely supports postdoctoral fellows, graduate students, and undergraduate research associates working on applications in nanoscience and engineering enabled by the foundational methods of nanofabrication. This support also goes beyond the principals Brett and Freeman, to seven other affiliated professors in ECE and Physics to whom incremental funding enables a significant increase in research activity, and fosters strong collaboration.

New initiatives and recognition in the last year include interim funding from Alberta Ingenuity to search for an Ingenuity Scholar in Nanofabrication, intended to bring together expertise in nanoscale engineering of soft and hard materials. Dr Freeman has spent much of his sabbatical year more firmly establishing collaboration between Nanocore and the National Institute for Nanotechnology, while developing new research efforts in the field microwave-frequency probes of microfluidic and nanomechanical systems. Dr Brett was recognized for his teaching contribu-

tions through the APEGGA "Excellence in Education Award" for 2004.

Alberta is closely connected to national developments in nanotechnology through the Nanoelectronics Program of the Canadian Institute for Advanced Research. According to Chaviva Hosek, CIAR President and CEO, the University of Alberta enjoys the highest participation in this program of any university in the world (CIAR also admits foreign associates). The Alberta members are Drs Brett and Freeman from Nanocore, and Dr Wolkow, the iCORE Chair recruited through Nanocore in 2002-03.

Former Nanocore personnel are playing key roles in Alberta nanotechnology development. PhD graduate Barb Djurfors has joined NuCryst in Sherwood Park, a firm developing nanostructured materials for health applications. PhD graduate and former Nanocore Research Associate Marek Malac has been hired by NINT as a Research Officer and group leader in charge of the excellent suite of electron microscopy tools. (Some of the electron microscopy capabilities at NINT, such as the sensitivity for electron holography, will be unparalleled in North America). Former research associate Mirwais Aktary operates the office for Raith nanolithography products in Edmonton and is developing advanced fabrication techniques through his spin-off company Applied NanoTools. Graduate student Peng Li is also a key member of Applied Nanotools. Norcada Inc. in Edmonton is leveraging the nanodevice fabrication skills of former graduate students Miro Belov and Mike Colgan through the AIIA program. PhD graduate Mary Seto has taken her expertise in microdevice processing to Micralyne. Daniel Salamon, an undergraduate student who has worked on nanofabrication for Nanocore for several years, is a Technical Officer at the National Institute of Nanotechnology. Wayne Hiebert is currently a NINT researcher seconded to the California Institute of Technology.



Michael Brett

RESEARCH PROGRAM OVERVIEW

The Nanoscale Engineering Physics Initiative and the ICE program have several interconnected themes. On the science side, the fundamental properties of the "building blocks" of future information technologies include nanomagnets and photonic crystals. Photonic crystal structures offer advanced control of the propagation of light and are a most promising technology for integrating high-level optical functionality onto chips. Conventional magnetic information storage methods have already evolved quite far into the "nano regime", and the potential for new technologies such as spin electronics and nanomagnetic logic is large. State-of-the-art nanofabrication capabilities are essential in order to make progress at the forefront of these areas, thereby establishing the second theme. For the ICE program we are also active in the engineering of real devices and the development of commercialization ready products and methods (such as fabrication of display devices and integrated nanosensors), to further the goal of spawning economic activity in Alberta in direct consequence of the Nanocore efforts. The formation of startup-company ChiralTF Devices based on the Glancing Angle Deposition (GLAD) nanofabrication process is an example of a small step in this direction.

RESEARCH PROJECTS

A primary Nanocore goal is to establish a critical mass of nanotech-related activity in the region. In their specific research and training activities, Nanocore personnel concentrate on the study of building block materials, methods, and components for nanotechnology. These developments underlie device applications in the ICE initiative.

Nanofabrication, utilizing the extensive facilities of NanoFab, continues to be a key focus of the research programs. In Brett's lab, complex structures are engineered in thin film coatings on the nanoscale utilizing the GLAD process developed and patented by Brett's team. These novel materials provide a focus and opportunities for team researchers to explore device applications where the nanoengineered structure and surface area provide advantages over conventional materials.

Recently Brett's group demonstrated fabrication of the first 3-dimensional photonic crystal in a square spiral geometry. These materials are of interest because of the potential promise in integrated optics devices, and because the square spiral architecture may offer advantages in ease of fabrication and manufacturability. A team of three graduate students (Martin Jensen, Mark Summers, and Jason Sorge) have made excellent progress in advancing our devices, by demonstration of greatly improved structural homogeneity, incorporation of intentional wave-guiding defects, and fabrication of crystals with operation close to the near infrared wavelength band utilized in optical communications.

In related optical device research, PhD student Andy van Popta and MSc student Matthew Hawkeye with collaborator Dr Jeremy Sit have developed a narrow band pass optical filter utilizing just one material but with a necessary refractive index variation engineered by variation in nanostructure. PhD student James Gospodyn provides precise characterization of these optical materials by spectroscopic ellipsometry, and Dr Doug Vick provides expertise on electrical characterization. In a fusion of optics, nanoscale engineering, and biology, graduate student Vikram Kohli and Dr Abdul Elezzabi are using ultra-short laser pulses to modify biological structure in cells.

Researching in collaboration with industrial partner Micralyne, MSc students John Steele and Shufen Tsoi, with professors Dr Jeremy Sit and Dr Jon Veinot, have demonstrated the operation of sensor devices with nanostructured surfaces that have been treated chemically or functionalized to optimize performance. For example, their humidity sensors – both optical and capacitive - afford greater sensitivity and significantly faster response than current commercial devices. Their demonstration of functionality to create hydrophobic surfaces opens the door to creation of sensors with chemical specificity.

Opportunities to apply ICT-developed nanotechnology to the energy field have been pursued by research associate Dr Greg Kiema and MSc student Doug Gish. They constructed Graetzel solar cells incorporating 20nm diameter nanofibres. These cells are based on porous nanostructured TiO_2 infiltrated with organic dye, and for efficient operation require a large TiO_2/dye interface surface area provided by nanofibres. It is hoped that photovoltaic conversion efficiencies can be improved by this approach.

Recent developments in nanofabrication in Brett's lab include nanostructure control of polymer materials of interest in plastic microdevices, fabricated in a templating process by PhD student Anastasia Elias, in collaboration with Dr Kees Bastiaansen of the Technical University of Eindhoven and Dr Dick Broer of Philips. PhD student Peter Hrudey has developed luminescent chiral materials, a potential component for more efficient polymer displays. Dr Maria Stepanova, with Dr Steven Dew, has developed new process to fabricate metal dots, networks, and nanowires on non-metallic substrates. Each of these processes brings new flexibility and control to nanomaterials engineering.

In Physics, there has been good progress in studies of new materials for information technology applications.

Michael Brett with some research team members at the 2005 Banff Informatics Summit

Ray Egerton and Frank Hegmann have worked on growth and characterization by electron microscopy of pentacene thin films, and physical studies of properties relevant to optoelectronic applications. Al Meldrum's group is making great strides in the development of silicon nanoparticle devices for optoelectronics. "Siliconization" has become one of the most dynamic topics in photonics.

Studies of the Si(100) surface at low temperatures, initiated with iCORE Visiting Professor Michael Horn von Hoegen, have been very fascinating. The silicon dimers which form at this surface represent an ultimately small limit of an electromechanical component. Each dimer tilts into one of two stable orientations, and switching between the two states may be induced by interaction with an STM tip. The STM has inspired suggestions to use this system for information processing (a model of an analogous two-state magnetic system was long ago mapped onto this mechanical system). Our studies have highlighted the importance of interactions between the surface dimers in this process, particularly along rows of dimers. These interactions are manifest in our observation of more than two conductance states when one is probing STM-induced transformations of the surface at low temperatures. In particular, the presence of "domain walls" (in the magnetics language) within dimer chains greatly facilitates transformations within the rows that contain them, and contribute to the appearance of additional conductance states as these topological defects pass through the tunnel junction. Significant modifications to the proposals for dimer logic may be required (including the possibility of domain wall logic, as has been discussed in the magnetic context). This effort has been spear-headed by Post Doctorate Fellow Yan Pennec with critical technical assistance from David Fortin.

Mark Freeman

Our studies of magnetization dynamics in confined geometries this year concentrated heavily on the magnetic oscillation modes of structures with circular symmetry (disks and rings). Such geometries are of interest for very high-density information storage because of their "closure" (they have very little stray field). In principle this will permit a higher density than for rectangular (bar magnet) storage elements. In order to record information in such an element one must be able to control whether the magnetization circulates in a clockwise or anti-clockwise fashion. We gained insight into the reversal mechanisms of nanorings through diffraction magneto-optical Kerr effect measurements. In small disks, Xiaobin Zhu discovered a surprisingly large frequency splitting of first-order magnetic normal modes, induced by the presence of a vortex core in a small diameter orbit about the center of the disk. Another exciting development in the magnetic area was a new joint project with the National Institute of Advanced Industrial Science and Technology in Japan, to further explore switching dynamics in nanomagnets. This project now has seed funding from the New Energy and Industrial Technology Development Organization (Japan).

We continued to study the dynamic coupling in magnetic multilayers with Bret Heinrich's group at Simon Fraser University. This work is also facilitated through the Nanoelectronics program of the Canadian Institute for Advanced Research, and experimentally addresses basic questions about the control of hybrid magnetic/non-magnetic structures for use in spin electronics. Dr Won Kee Kim, a Nanocore and NSERC supported Post Doctorate Fellow working with Professor Marsiglio has been performing fundamental calculations related to the underpinnings of spin electronics, addressing such questions as, "how many electrons are needed to flip a single spin?"

Another exciting stride in our general focus area of high speed local probes has been made by Markus Walther in Frank Hegmann's laboratory, who has succeeded in coupling terahertz electroagnetic radiation (triggered by ultrashort laser pulses) onto metal-tip antennas. This work is also sponsored by the NSERC NanoInnovation Platform.

OBJECTIVES FOR NEXT YEAR

The research programs will continue to focus in three areas: improving our abilities to engineer and fabricate precise nanostructures, such as nanomagnetic building blocks or chiral (helical) photonic crystals; improving characterization techniques through the use of low temperature ultrahigh vacuum scanning tunneling microscopy (LT-STM); and developing applications of nanoengineered devices in ICT and other fields of importance to Alberta.

The capability of nanostructure engineering to provide functional materials for photonics, sensor and ICT devices will be explored, with efforts aided by the installation of a new $300k high-vacuum thin film deposition system which will provide considerable new capacity for fabrication. Combined with the facilities of NanoFab, essential tools and processes are in place for each critical step ranging from blanket thin film deposition to nanoscale patterning to device testing.

One area of research emphasis will be photonic materials and devices. Development of promising 3D square spiral photonic crystals will be extended towards fabrication of devices and waveguides, with an ultimate long term goal of demonstrating optical functionality on a chip. Chiral, birefringent and luminescent nanostructured materials will be optimized to a stage where potential application in flat panel displays can be evaluated. In these latter efforts, we will be assisted by collaborator Dr Dick Broer of Philips Research Labs, who will spend the summer of 2005 visiting Brett and his colleagues. In related photonic device work, we plan to make optical filters with improved functionality, geared to potential applications in sensor devices and electrically switched optics devices.

Improved methods of fabricating nanostructured materials will continue to be studied. Specifically it is intended to optimize the template process utilized to create novel chiral structured polymers, and to utilize these polymers in prototype devices. The modified GLAD process for fabricating 20nm diameter fibres will be utilized in applications studies where high surface area and precisely controlled nanostructure geometries are required.

A nanoengineered materials research effort, though focused on ICT fields, often presents exciting opportunities outside the direct ICT area that cannot be ignored. Utilizing ICT-derived nanofabrication has led to development of fast response humidity sensors, and progress in optimizing Graetzel solar cells. Utilizing our fast response device and nanostructure geometries, a broader range of sensor devices will be explored, with strong encouragement from the industrial partner Micralyne. The utility of nanofibres incorporated into solar cells will be evaluated to determine if further efficiency improvements are possible. Prospects for commercialization will be evaluated by Micralyne/University of Alberta spinoff ChiralTF Devices Inc.

Mark Freeman with some research team members at the 2005 Banff Informatics Summit

Focus will also be on modifying some of the techniques Freeman's group has developed for studies of micro- and nanomagnetic dynamics, for applications to nanomechanical and fluidic systems. The current world's record for the highest frequency nanomechanical resonance studied is barely above 1 GHz. This is very impressive, but it should be possible to significantly surpass this milestone using stroboscopic optical techniques. This capability will create many exciting new opportunities, including the investigation of coupling between magnetic and mechanical normal modes of oscillation in nanostructures. It may be possible to mechanically tune the damping of ferromagnets, and perhaps even to mechanically induce magnetization reversal.

Our work on microwave electrical probes of material in microfluidic environments, in collaboration with NINT and with Prof. Douglas Thomson at the University of Manitoba (and some additional interaction support from CIAR), is also expanding. An internship student, Steven Olson, has been hired through NINT to ramp up chip production for this project over the next 16 months.

We will continue our studies of magnetization dynamics in confined structures. Initially there will be an emphasis on spectroscopy of normal modes as a function of applied magnetic field. Laterally-patterned multilayers will be investigated, with specimens prepared locally and from SFU. We will work towards an expansion of the NEDO-sponsored collaboration beyond the initial seed project.

The scanning tunneling microscopy project will continue with basic studies of nonequilibrium phenomena on the Si(100) surface at liquid helium temperatures. We have begun to look at the effect of small molecule absorbates on this surface. Starting towards the end of calendar year 2005 the condensed matter physics laboratories will begin the move to new physical space in the Centennial Centre for Interdisciplinary Sciences, Phase I. We are looking forward in particular to installing our low temperature ultrahigh vacuum scanning tunneling microscope in this new environment. Our effort on spin-polarized tunneling and towards dynamics resolved at the level of individual spins by STM will commence after the move.

RESEARCH TEAM MEMBERS

Team Leaders

	ROLE /TOPIC	AWARDS/SPECIAL INFORMATION
Dr Michael Brett	iCORE Professor and iCORE/NSERC/ Micralyne Industrial Research Chair, Canada Research Chair	ASTech Award for Outstanding Leadership in Alberta Technology (2003) Associate Member, CIAR Program in Nanoelectronics (2002)
Dr Mark Freeman	iCORE Professor, Canada Research Chair	Associate Member, CIAR Program in Nanoelectronics (1999)

Faculty Team Members

	ROLE /TOPIC	AWARDS/SPECIAL INFORMATION
Dr Steven Dew	Microfabrication Process Technology	
Dr Abdul Elezzabi	Ultrafast Photonics	McCalla Professor Canada Research Chair in Ultrafast Photonics and Nano-Optics
Dr Jeremy Sit	Nanostructured Devices	
Dr Ray Egerton	Electron Microscopy of Thin Films	MSA Award
Dr Frank Hegmann	Terahertz Spectroscopy	
Dr Frank Marsiglio	Superconductivity	
Dr Al Meldrum	Nanoparticles and Nanomaterials	

Postdoctoral Fellows

	ROLE /TOPIC	AWARDS/SPECIAL INFORMATION
Dr Xiaobin Zhu	Ultrafast Microscopy	Ingenuity Fund Fellowship
Dr Yan Pennec	Local Dynamics at Silicon Surfaces	
Dr Jim Broughton	Supercapacitors	
Dr Greg Kiema	Microfluidic Materials	
Dr Doug Vick	Nanostructure Growth	
Dr Wonkee Kim	Quantum Mechanics of Spin Transfer to Nanomagnets	
Dr Maria Stepanova	Ion Beam Nanostructuring	
Dr Marcus Walther	Near-field Terahertz Spectroscopy	

PhD Students

	ROLE /TOPIC	AWARDS/SPECIAL INFORMATION
Grey Arnup	Single-shot Ultrafast Microimaging	
Miro Belov	Magnetic “Ripple Tanks”	
Jason Blackstock	Nanoscale Molecular Device Fabrication	NSERC Julie Payette
Robert Bryce	Colloids in Microfluidics	NSERC PGSD
Kristen Buchanan	Ferromagnetic Nanocomposites	NSERC PGSD, Steinhauer
Zhigang Liu	Magnetic Modes in Confined Structures	
Allan MacDairmid	Bio-inspired Macromolecular Nanowires	NSERC PGS-B
Barb Djurfors	Nanostructure Characterization	IW Killam Scholarship
James Gospodyn	Chiral Optic Ellipsometry	
Peter Hrudey	Luminescent Nanostructures	NSERC PGSD; iCORE
Anastasia Elias	Replica Nanostructures	NSERC CGSD; Ingenuity; iCORE
Martin Jensen	Photonic Crystal Devices	Ingenuity; iCORE
Andy Van Popta	Chiral Photonic Devices	NSERC CGSD; iCORE
Mark Summers	Photonic Crystal Materials	NSERC PGSD, Ingenuity, iCORE

MSc Students

	ROLE /TOPIC	AWARDS/SPECIAL INFORMATION
Doug Gish	Nanofibre Devices	NSERC PGSM, Ingenuity, iCORE
Matthew Hawkeye	Photonic Filters	Province of Alberta Scholarship
Jason Sorge	Photonic Crystal Wave Guides	Province of Alberta, NSERC PGSM
John Steele	Sensor Devices	NSERC PGSD
Paul Moffat		MSc

Other Team Members

	ROLE /TOPIC	AWARDS/SPECIAL INFORMATION
Dr Mohammed Hedayatipoor	Microwave Dielectric Measurements of Proteins	Visiting Professor
Dr Marek Malac	Electron Holography and Lithography	NINT
Dorothy Fan	Nanofabrication Control Systems	Research Associate
Nick Wakefield	Student Researcher	NSERC Summer Student
Sumudu Fernando	Summer Student Researcher	NSERC Summer Student
Tze Luck Chia	Summer Student Researcher	NSERC Summer Student
Kevin van Popta	Summer Student Researcher	NSERC Summer Student
Delphine Lagarde	Summer Student Researcher	
Cindy Blois	Summer Student Researcher	NSERC Summer Student
Stephen Yewchuk	Summer Student Researcher	
Karin Hayward	Administrative Assistant	
Ben Bathgate	Technician	
Stephenie Bozic	Nanofabrication Specialist	
Lynn Chandler	Administrative Assistant	
David Fortin	Administrator/Technical	

Nanocore Supported Graduate Students of Affiliated Researchers

	ROLE /TOPIC	AWARDS/SPECIAL INFORMATION
Shufen Tsoi	Surface Functionalization	
Vikram Kohli	Femtosecond Laser Nanobiotechnology	
Lucian Covaci	Numerical Simulations of Surfaces and Nanoscale Superconducting Devices	
Fatih Dogan	Electron-phonon Systems using DMRG Method	
Aaron Hryciw	Silicon Nanocluster Photonics	NSERC CGSD, Andrew Stewart Prize, Steinhauer
Nicole MacDonald	Silicon Nanocluster Photonics	Province of Alberta
Peng Li	Radiation Damage to Organic Compounds	
Aaron Slepkov	Nonlinear Optical Properties of Organics	NSERC PGS B
Simona Verga	Researching Nanoscale Superconductivity	
Feng Wang	Magnetic Nanoparticles	Killam Scholarship
Hui (Julie) Qian	Magnetic Nanoparticles	

COLLABORATIONS

PARTICIPANTS	PARTICIPANTS	NATURE OF COLLABORATION
PROVINCIAL		
University of Alberta: Mech Eng	Dr W. Finlay, Dr C. Lange	Fabrication of Nanoengineered Aerosol Particles
University of Alberta: ECE	Dr R. Fedosejevs, M. Taschuk, Dr Y. Tsui	Optical Characterization of Nanostructures
University of Alberta: ECE	Dr K. Westra	Nanostructured Inorganic Materials
University of Alberta: Chem Eng	Dr D. Ivey	Structural Characterization of Nanostructures
University of Alberta: Medicine	Dr J. Acker	Cell Nanosurgery
University of Alberta: Chemistry	Dr J. Veinot	Integrated Sensor Devices
University of Alberta: Chemistry	Dr J. Harrison	Fabrication of Nanopores for Microfluidics
University of Alberta: Chemistry	Dr J.B. Green	
	Dr M. McDermott	Conductive Probe Atomic Force Microscopy
University of Alberta: Physics and Chemistry	Dr F. Hegmann Dr J.B. Green Dr R. Tykwinski Dr R. Wolkow	Molecular Conductors
National Institute Nanotechnology	Dr J Buriak	Nanostructured Ge
PARTICIPANTS	PARTICIPANTS	NATURE OF COLLABORATION
NATIONAL		
Carleton University	Dr T Smy	Nanostructure Growth Modelling
McGill University	Professor P. Grutter	
University of Toronto	Dr S Clemdenning Dr I Manners	Direct-written Organometallic Nanomagnets
University of Manitoba	Dr D Thomson	Small Volume Dielectric Measurements
Simon Fraser University	Dr B Heinrich	Dynamic Coupling in Magnetic Multilayers
INTERNATIONAL		
Philips Research Corporation	Dr D Broer	Study of Nanostructure Liquid Crystal Devices
Technical University of Eindhoven	Dr K. Bastiaansen	Polymer Nanostructures and Devices
Brown University	Dr G. Crawford	Optimizing Liquid Crystals in Nanostructures
National Institute of Advanced Industrial Science and Technology in Japan	Dr Hiro Akinaga	Switching in Nanoscale Magnets
Institut fur Laser und Plasma-physik, Univ Duisburg-Essen	Dr Horn von-Hoegen	Dynamics of Electrons in Nanostructures

INTELLECTUAL PROPERTY

PATENTS	TITLE/NAME	STATUS
DE 69808653, EP1007754B(UK), EP1007754B(FR)	Glancing Angle Deposition of Thin Films	Granted prior to this year
US 5,866,204	Method of Depositing Shadow Sculpted Thin Films	Granted prior to this year
US 6,206,065	Glancing Angle Deposition with Controlled Porosity	Granted prior to this year
US 6,248,422	Shadow Sculpted Thin Films	Granted prior to this year
US 6,549,253	Optical Device	Granted prior to this year
WO9803695	Capped Porous Thin Films	Granted prior to this year
WO9906608	Glancing Angle Deposition of Thin Films	Granted prior to this year
CA 2,182,452	Shadow Sculpted Thin Films	Under review
CA 2,237,732	Glancing Angle Deposition of Thin Films	Under review
JP 2001502013	Capped Porous Thin Films	Under review
JP 2002509188	Glancing Angle Deposition of Thin Films	Under review
US 9-13453-63 USPR	Photodisruption Process For Manipulating Cells	Under review
SPINOFF COMPANIES		
Chiral TF Devices		In product development stage

Micralyne and the University of Alberta have existing agreements that protect certain IP developed in the research programs of Michael Brett. This IP includes:

- the GLAD fabrication process
- improvements to the GLAD fabrication process
- applications utilizing GLAD-fabricated materials
- hybrid liquid crystal/GLAD devices

FUNDING

Michael Brett and Mark Freeman use NSERC money (~$487K) to fund research on their team. In addition, they each hold an iCORE Professorship and a Tier 1 Canada Research Chair ($200K/year). Dr Brett also holds an iCORE Industrial Chair ($100K/year) award. This year their team received substantial funding from CFI (~$6.1M) and ASRA (~$4.9M) and as well as funds from Western Economic Diversification Canada($483K).

PUBLICATIONS

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NANOSCALE INFORMATION AND COMMUNICATION TECHNOLOGIES

iCORE Chair
Physics, University of Alberta
and
Group Leader
Molecular Scale Devices
National Institute for Nanotechnology
National Research Council of Canada

Photo courtesy of the National Research Council of Canada

ROBERT A. WOLKOW

http://www.phys.ualberta.ca/~wolkow/

The Molecular Scale Devices Group addresses key issues facing future molecular device technologies. We use scanning tunneling microscopy (STM) and advanced quantum mechanical computation, together with in-group expertise in organic synthesis, condensed matter physics, surface chemical physics and instrument engineering to gain a detailed understanding of and atom-scale control over hybrid silicon-molecule structures. Our involvement in the study of molecules as devices began approximately 15 years ago, where our early work helped define the concepts and methods that opened up a new field. Three of our early papers have collectively been cited over 860 times; a more recent article, proposing hybrid silicon-organic molecular structures as a foundation for molecular devices has received over 175 citations, placing it in the top 1 percent of articles in the field.

EXECUTIVE SUMMARY

The benefits of silicon technology are well known. The beauty of molecules as building blocks is that they come preconfigured with desired properties (flexibility, chemical affinity, light absorption and emission spectra, electron affinity, etc.) – and those properties can be put to work by "docking" the molecules and electrically connecting to them. By addressing the difficult problems associated with precisely connecting molecules to silicon, we believe new function will be created through this hybrid approach. Our team has developed the first and only method to have molecular nanostructures self-assemble. Unlike other previous processes that employ weak physical interactions, ours creates robust, covalently bonded, elevated temperature stable entities.

Self-assembly is a supporting pillar of future nanotechnologies – nanostructures will only be harnessed if they more or less make themselves. We therefore need to create such automatic processes. Our method allows one to precisely and (relatively) easily create molecular nanostructures by essentially pointing to the spot where auto-fabrication is desired. Our process also allows for parallel fabrication of many structures simultaneously – we are not limited to a slow serial process.

In our second year, we have moved beyond the start-up phase to see exciting progress. Numerous developments were made, as itemized below, but one possibly revolutionary development stands out. We have succeeded in demonstrating a new concept for a single molecule transistor. We have a patent pending and the work will appear in the 2 June issue of the journal Nature.

For this review period one further patent is pending and one patent was granted. In the past year 13 new papers were published and 15 invited lectures were delivered.

RESEARCH PROGRAM OVERVIEW

Our team is following a program of study designed to discover hybrid silicon-molecule properties that would underpin revolutionary new devices.

The "tools of our trade" include wide ranging surface analysis (primarily with ultra high vacuum scanning tunneling microscopy), extensive quantum mechanical modeling (in-house and via external collaborations) and some chemical synthesis. In each of those areas, a portion of the effort goes toward new instrument and method development.

Self-Directed Growth

We continue to work on, and continue to lead in the area of self-directed growth of molecular nanostructures on silicon. In the past year we added new elements of atom-scale control. Also, a fundamentally different driving force for self-directed growth has been discovered, enabling a much broader range of molecule types to be added to silicon.

Connections to Nanostructures

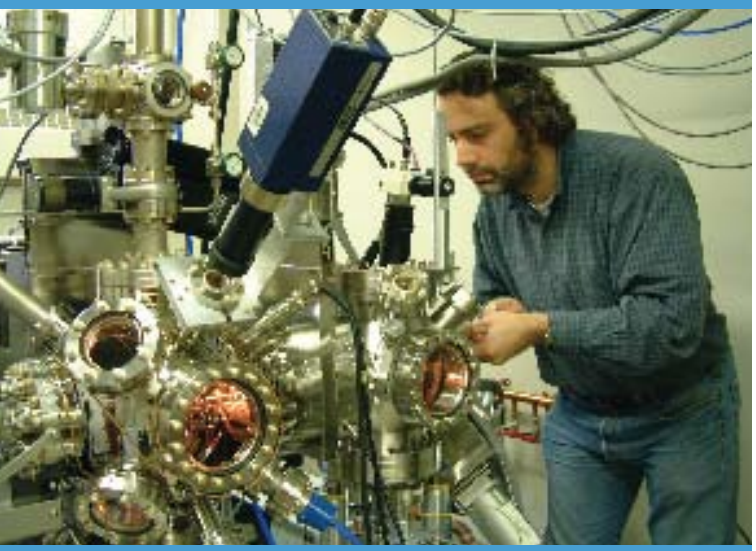
In order to use nanostructures we must find means to address them – to get information to them and from them. Most reports to date have suffered from having ill-defined connections. We are continuing various new contact studies.

Other Directed Growth

A variety of schemes (distinct from the self-directed growth work described above) for efficient, controlled growth of nanostructures are being explored. Our team has performed theoretical studies to determine, for example, how to steer a growth process with electric fields. This remains a key area of interest. Our new multi-probe instrument (the "connected STM") described below, will enable that work.

Theory

Theory is integrally important in all we do. As before, on-going efforts involve determinations of adsorbate geometries, spectra and STM images. This year modeling of electric field shifting of molecular energy levels was one of our primary concerns. That work allowed us to provide a detailed, quantum mechanical description of our single molecule transistor concept.



Team member Paul Piva at work in the lab

Last year, as planned, we gained the ability to perform classical calculations to describe band bending and other field effects. We are now able to describe atom-scale and macro-scale features of our systems of study. This is a key step toward harnessing small entities to make practical devices.

Transport (conduction) characteristics of our hybrid organic silicon structures are maturing. As a result, we now have the first robust indication that our molecular lines are indeed molecular wires – an exciting development.

Toward Spin-Offs and Economic Impact

In the past, though our work has been suggestive of practical functions, we were unable to see a path to applications. With the extraordinary team and facilities now assembled, we see a remarkable change. Several patent applications and practical tests are underway. This great change in our ability to have an economic impact would not have been possible without iCORE.

We continue to explore device concepts. Because a direct route to molecule-based ICT technologies seems impossible today, we aim for stepping stones, like sensors, and from there to move toward other electronic and logic functionality. Molecular sensing applications will be both a lucrative end, and a stepping stone to more complex devices such as molecular computers.

RESEARCH PROJECTS

Self-Directed Growth

Our team has further refined control over the assembly process. For example, our paper "Protection-Deprotection Chemistry to Control Styrene Self-Directed Line Growth on Hydrogen-Terminated Si(100)" describes the ability to halt the growth of all but a single targeted structure. Furthermore, the ability to restart growth at that area is shown. This work demonstrates a new ultra-fine level of control over the fabrication of molecular nanostructures. It is important to note that we have achieved this added control via automatic chemical means not arduous physical means. This distinction is important - such chemical processes as we are developing allow "parallel" application to numerous structures where as physical processes developed previously only allow serial and therefore very slow fabrication. We seek useful structures that almost make themselves.

Our study, "Dispersion Interactions Enable the Self-Directed Growth of Linear Alkane Nanostructures

Covalently Bound to Silicon" greatly changes the scope of our nanostructure growth process. Where previously we could only attach molecules containing particular chemical functional groups, we have now discovered that a much wider range of molecules can be caused to undergo self-directed growth processes. The range of properties we can lend to a silicon surface are therefore greatly enhanced.

Connections to Nanostructures

Atom-Scale Metal-Silicon Contacts

Our team has done extensive studies of atom-scale metal-semiconductor contacts. An understanding of such contacts is required to better characterize the silicon-molecule hybrid structures we create. Our research showed that anomalously low Schottky barriers result from such small area contacts - although we later found out that others came to this conclusion less than one year before us, we still see practical implications of this knowledge and have found no patent covering the idea. This work started with visiting Professor Burghartz. He has now fabricated next-generation structures to further explore our contact ideas. With positive results, this work continues.

"Connected STM"

Our multi-probe scanning tunneling microscope has progressed greatly. Key software, mechanical and electronic elements have been designed, built and proven. This instrument, due to be operational in less than one year, will allow numerous new experiments.

Concept for a Single Molecule Transistor

Making a molecular transistor is difficult for a number of reasons. A molecule is very small and therefore difficult to address with three electrodes. Our team has managed to gain three effective connections with only two electrodes, by attaching a molecule to a silicon substrate. We have managed to have a single silicon atom on that substrate become charged, or not charged, with a single electron. The molecule simultaneously experiences the connection to the substrate, and feels the field due to the localized charge. An electrode placed over the molecule provides the third connection. When a charge is present, molecular electronic energy levels shift into alignment with levels of the electrodes, allowing conduction through the molecule. When the charge is absent, conduction ceases.

Theory

Theory, primarily performed by Dr Gino DiLabio, has been a part of virtually all of our projects. Also, our collaborator, W.Hofer/Liverpool, has participated in our single molecule transistor concept paper. Another partner, G.Kirczenow/Simon Fraser University, has nearly completed calculations that reveal the electronic workings of our molecular lines, which will be soon presented in a joint paper. We now have substantial evidence that our lines are indeed wires, substantiating our earlier speculation that our molecular lines could allow interconnections on the very smallest scale.

The above development provides an example of how our rational plans (and best guesses) are moving inevitably toward powerful new ICT related technologies.

Robert Wolkow and some research team members at the 2004 Banff Informatics Summit

Team member Janik Zikovsky brings the in-house ability to describe charges, fields and the response to those of silicon and molecule energy levels. This compliments our microscopic quantum mechanical calculations. It allows us to describe macro-scale properties resulting from nanoscale features - a key step toward harnessing small entities to make practical devices.

In among this year's publications are several works involving complexities of chemical reactions and theoretical methods. These should be regarded as "tools development". These have an indirect but important connection to our ICT directed work.

Toward Spin-Offs and Economic Impact

Ultra-fine lithography

We are studying new electron-resist materials and nano-scale lithographic procedures. New opportunities have since emerged as described below.

Nano-tips

We have discovered a process for fabricating what we believe to be the sharpest objects ever made: tungsten probes with a radius of curvature of less than 1 nanometer. We create these with a field and chemical-assisted spatially confined etching process. We have found no precedent for the process and a patent is to be filed imminently. The nano-tips are being tested by Hitachi with whom we have a non-disclosure agreement. We hope these will be exquisite electron emitters in transmission and scanning electron microscopes. Other applications will be tested in the coming year.

Single Molecule Transistor

Our new concept for a single electron transistor now has patent pending status (a provisional patent was filed).

Noise Reduction Devices

We continue to explore noise reduction techniques with Professor Sun from Calgary, which could have numerous applications. We will apply these tools in our lab in the near term. Collaborative further development will continue. We believe these tools will find wider application because nanoscale measurements and fabrication generally require isolation from background vibrations and we are speculating that ultra-fine (neuro) surgery procedures could benefit from our approach.

Connected STM

Our multi-probe scanning tunneling microscope will redefine the state of the art in scanned probe microscopy, which has commercial possibilities through licensing the system or aspects of our design to an instrument manufacturer.

Prototype Silicon-Molecular Device

We continue to work to identify the key physical processes in making a prototype silicon-molecule device; a pressure sensor.

Patented Anti-Oxidant

Dr Gino DiLabio received US patent #6,835,216 for a novel class of chain-breaking antioxidants. These new antioxidants were first designed on a computer using methodologies developed by DiLabio, then synthesized at Vanderbilt University and tested

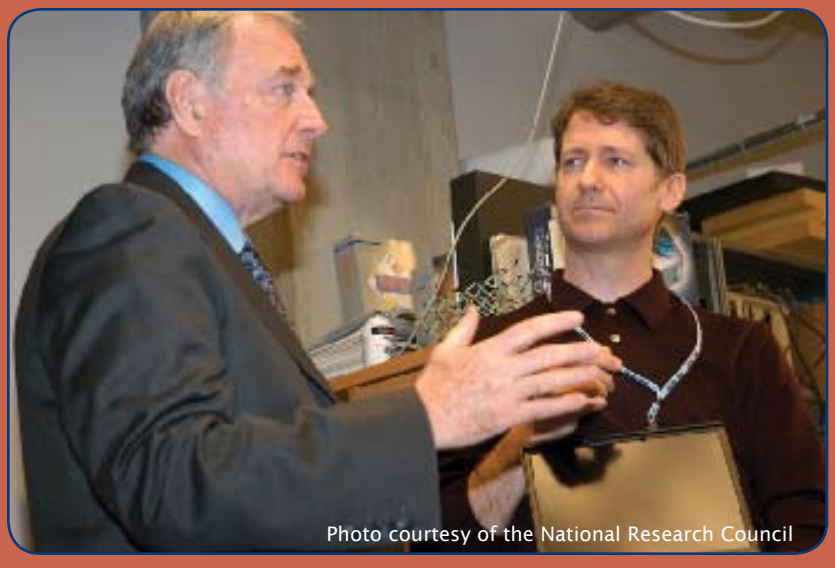


Photo courtesy of the National Research Council

Robert Wolkow touring Prime Minister Paul Martin through the NRC facilities

against vitamin E at the University of Bologna. These compounds react at rates that are higher than any known antioxidant. Other studies of antioxidant systems were undertaken. Various applications are being tested.

OBJECTIVES FOR NEXT YEAR

Self-Directed Growth Combined with New Characterization Methods

The self-directed growth phenomena will be central to our studies. We will seek refined control over the process and move toward further electrical characterization of the molecular lines we can now make. We are testing a process for sensitively measuring surface "leakage" currents. If successful, these will allow the electrical transport properties of molecular films and nanostructures to be measured rather easily.

Our soon to be completed multi-probe s will allow numerous previously impossible experiments at the nanoscale. In one mode of operation, two (or more) independently moveable probes will contact a surface. The probes will be viewed though a scanning electron microscope. Spacing of probes may be as close as several 10s of nanometers. These probes will allow highly local electrical characterization. Yet another probe, with high resolution STM imaging and manipulation capability will view or alter the region near the electrical probes, allowing atom-scale monitoring and modification, while simultaneously gaining electrical characterization of that nanoscale hybrid molecule-silicon structure.

Molecule-Molecule Tuning

Our methods for assembling and viewing molecular assemblies creates a unique opportunity for exploring the nature of intermolecular and molecule-substrate coupling. In unpublished work, we have revealed the ability to watch as individual molecules have their properties tuned in response to particular juxtapositions with other selected molecules. This is a unique and remarkable opportunity to explore fine tuning of chemical and electronic properties of molecules. To give one example, we suspect that particular compositions will allow us to make molecular diodes that are laterally connected to a silicon surface and which will allow integration with other surface entities - possibly another useful building block in future molecular devices.

Tuning Local Electronic Structure – "Alchemy"

We believe we have the capacity to locally tune the electronic and chemical character of single atoms. This is like alchemy in that a single element can be caused to act differently as a result of external controls. We are certain we can achieve this (results are not yet published) via local chemical means. We will attempt to do something similar via totally electrical means. Literally, we aim to change the nature of an atom by the turn of a button. This will have many implications.

Localizing and Manipulating Single Electrons

We have indications that we can controllably "place" single electrons with atom-scale spatial control and speculate that this might lead to the ability to poise groupings of electrons and allow them to interact – or "compute". We expect to gain demonstrations of our ability to localize charge in the coming year.

Connections to Nanostructures and Exploratory Devices

We aim to complete our molecule sensing contact studies, and pursue a patent.

Theory

Single Dopant Atoms

We foresee having the ability to describe the behavior of single dopant atoms in nanoscale pieces of silicon. This work will lead to a predictive capability and the capacity to design new types of dopant species. We are hoping to create surface bound dopants – not conventional substitutional dopants. One attraction of our approach is that doping could be achieved without thermal activation, which partially destroys the spatial definition of a doped region.

Transport theory

Transport analyses will continue, with George Kirczenow, likely also with Hong Guo from McGill, and also using our developing in-house capabilities. It is crucial that we continue to push toward meaningful characterization of our hybrid nanostructures. In particular, we hope to describe variations on our new transistor concept (already covered by our patent). We have in mind configurations that more readily allow multiple, single-molecule transistors to be combined to form an integrated circuit.

Supriyo Datta of Purdue is currently working on a theoretical model to describe our new transistor concept, which will likely become a collaborative effort. In any case, further understanding should emerge.

Extending Classical Poisson's calculations to non-equilibrium

As stated above, we now have in-house capacity to apply Poisson's equation to our multi-component systems. The next and crucial step is to consider non-equilibrium conditions. Present methods do not allow for perturbations caused by electron current. We are exploring teaming up with Randy Feenstra of Carnegie Mellon who has welcomed our involvement and is well along toward solving that problem. This is another step toward solving the relevant problems that can move lab concepts toward devices.

Furthermore, a new professor at University of Alberta, Mani Vaidyanathan is very interested in novel device concepts. We have begun discussions. He may be able to join in the effort. We hope to build/promote local strength in this area.

Other Directed Growth

New schemes for directing nanostructure growth have been planned. The aim is to develop a field-directed process. Lithographic strategies have been abandoned for now. Our new multi-probe STM will allow first tests to be done in approximately one year. This new tool will allow local fields to be created with auxiliary electrodes (tips).

Outreach

The following section describes some community outreach activities undertaken by the Chair in order to make our work and research, accessible to the public and our stakeholders.

Meeting with Prime Minister and Deputy Prime Minister

In March, the Chair toured Prime Minister Martin and Deputy Prime Minister McLellan through our facilities. Both visitors were clearly engaged and knowledgeable. We subsequently spent approximately one hour, together with several other University of Alberta scientists, the Director General of NINT and the presidents of the University and of NRC discussing a wide range of topics (photo on page 138).

Essay contest

The Chair helped judge a science essay contest for grade 6, 7 and 8 students in Alberta.

Philosopher's café

The Chair gave a public talk, in the Edmonton public library central branch, on nanotechnology together with co-presenter, Lori Sheremeta of the University of Alberta Health Law Institute.

iCORE Public Forum

Together with other iCORE profs and chairs, the Chair engaged in a public forum at University of Alberta related to future nanoscale technologies and their impact on current microtechnologies.

Edmonton Strathcona High School

A team member spoke to advanced placement students about nanotechnology.

Discovery Channel

Robert Wolkow with Discovery Channel host Jay Ingram

On June 1, 2004 we had Jay Ingram of the Discovery Channel's "Daily Planet" program visit our lab. A nice segment was recorded and shown repeatedly gaining much recognition for University of Alberta and NINT.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

Research Team Members

TEAM LEADER	ROLE / TOPIC/OTHER INFO
Dr Robert Wolkow	Team Leader
	Professor in Physics at University of Alberta, Principal Research Officer and Molecular Scale Devices group leader at National Institute for Nanotechnology (NINT), NRC and adjunct Professor of Chemistry.
	In addition to directing all activity stated below, Wolkow has a managerial role at NINT.

TEAM MEMBERS	ROLE / TOPIC/OTHER INFO
Judy Xu	Group administrator
Dr Jason Pitters	Permanent NRC staff scientist at NINT, experimentist, specializes in scanning tunneling microscopy and atom-scale control of surface chemical modifications of silicon
	Responsible for all ultra high vacuum scanning tunneling microscopy and related laboratories, and as well, for day-to-day guiding of postdocs and supervising group technician. Liaises extensively to make our group's particular expertise more widely accessible to the local community.
Dr Gino DiLabio	Permanent NRC staff scientist at NINT, theorist working on quantum mechanical calculations of molecular and silicon surface calculations to reveal electronic and chemical properties
	Manages group's computer cluster facility, aids in institute and university (Westgrid) computer facility management, supervises graduate students, liaises extensively to make our skills available to the wider community. DiLabio was named an "Innovative Albertan" and appeared in the Alberta Government Innovation and Science 2005 calendar.
Mark Salomons	Contract employee, Instrument Design Engineer, designs state of the art instruments that cannot be purchased, giving us an experimental lead, and opening the door to commercialization opportunities.
	Salomons is designing a new multi-probe nanoscale scanning and measurement tool. We will be able to simultaneously monitor and/or manipulate matter on the atomic scale, while also measuring electrical transport properties. This machine will give us a lead in the world in our ability to gain practical measurements relating the nano-scale to the macro-scale world. This is a key step toward discovery of new device concepts.
Martin Cloutier	NRC Technical Officer
	Wide ranging technical support

POSTDOCTORAL FELLOWS	
Paul Piva	Last year I said "We are hopeful of a breakthrough soon …" Piva's studies of molecule-silicon interactions have indeed provided the primary impetuous for our dramatic development of a single molecule transistor. We have a patent pending. A publication in Nature is coming in June.
Mohamed Rezeq	Creates ultrafine probes and studies nanoscale electrical contacts to silicon. Hitachi USA and Japan are involved (a non-disclosure is in place) in evaluating our extraordinary tips as superior electron field emitters. Publication was delayed while a patent sought. We soon will have a patent pending.

Adam Dickie	Studies nanoscale electrical contacts to silicon, as mediated by molecular adsorbates. Molecular sensing has been achieved. We are researching patent prospects.
Stanislav Dogel	Installed new combined scanning tunneling microscope, electron energy loss spectrometer; a powerful new tool that gives us an edge in sensitive surface analyses (perhaps two or three similar machines in the world).
Iana Dogel	Studies chemical processes for creating atomically-defined molecular nanostructures on silicon and has found a new species capable of depositing single H atoms on a surface — an important step toward full nanostructure fabrication control.
PHD STUDENTS	
Janik Zakovsky	Aids in new instrument development, calculates electrostatic field effects on silicon bands and adsorbed molecules, and prepares to study nanoscale transport phenomena. A brilliant student.
MSC STUDENTS	
Amsalu Anagaw	Quantum mechanical calculations of molecule-silicon systems
SUMMER STUDENTS	
Brian Olsen	A top student from University of Alberta Eng Physics program, aids in instrument development — establishing process for fabrication of piezoelectric force — sensing electrical contact probes
Manuel Smeu	A top quantum chem. student from Carelton University, likely to join us as MSc student. Quantum mechanical calculations of molecule-silicon systems.

COLLABORATIONS

PARTICIPANTS	NATURE OF COLLABORATION
PROVINCIAL	
Professor Mark Freeman, Physics, University of Alberta	A joint effort exploring ultra fast scanned probe microscopy — Freeman brings time-resolved scanned probe and magnetism expertise.
Professor Frank Hegmann, Physics, University of Alberta	The same joint effort as above to explore ultra fast scanned probe methods, Hegmann brings ultra fast laser expertise
Professor John-Bruce Green, Chemistry, University of Alberta	Exploring methods for creating defect-free chemically modified silicon surfaces through wet chemistry technique, rather than in ultra-high vacuum
Professor Rik Tykwinski, Chemistry, University of Alberta	Exploring highly electrically conjugated molecules as candidate molecular wires, and more
NATIONAL	
Professor George Kirczenow, Physics, Simon Fraser University; renowned mesoscopic physics and transport theorist.	Coupled experimental-theoretical electrical transport study of hybrid silicon-molecule structures, a paper is near completion.
Professor Qiao Sun, Electrical Engineering, University of Calgary; expert in control systems, finite element analyses and robotics.	We are designing new instrument noise isolation techniques. Our instrument is — and much of future nanoscale engineering will be — extremely noise sensitive. A joint grant is being sought. SKF Magnetic Bearings Ltd, Calgary, is a partner. Our engineer Mark Salomons works closely with Dr Sun. Two graduate students from Calgary have worked on the project also.
K. U. Ingold, Steacie Institute for Molecular sciences, NRC	Radicals and solvent effects

INTERNATIONAL	
Professor D. Pratt, University of Illinois, Champagne-Urbana Professor L. Valgimigli, University of Bologna	Antioxidant chemistry
Professor P. Christiansen, Clarkson University Dr M. Hurley, US Army Research Labs	Quantum capping potentials
Dr J. Walton, St. Andrew's Dr P. Mulder, Leiden	Radicals and solvent effects
Professor Werner Hofer, Physics, Liverpool	Theoretical study of molecule-silicon electronic properties — a coauthor on our upcoming Nature publication. Werner's theoretical approaches compliment ours (DiLabio's).
Professor Dr Joachim N. Burghartz, Scientific Director DIMES, Delft University of Technology: Professor Burghartz is himself an expert and active researcher in the area of advanced silicon technologies. He was for approximately one decade a researcher at the IBM T.J. Watson Research Center at Yorktown Heights New York.	We discovered anomalously low Schottky barriers for atom-scale metal-silicon contacts. Two papers will come of this work, patent prospects are being considered. Initial measurements employed STM. Now a practical (lithographically prepared) test structure has been (and continues to be) fabricated and so far is promising.

INTELLECTUAL PROPERTY

PATENT TITLE	STATUS
Synthesis of nanostructures covalently bonded to silicon surfaces	University of Alberta tech transfer group judged the work too far from commercialization to merit patent.
Molecular transistor	Patent pending
Nano tips	Patent pending
Chain-Breaking Antioxidants	US patent no. 6,835,216, December 28, 2004.

FUNDING

Robert Wolkow received a combined total of ~$1.4 M from NSERC, NRC and CIAR to use for research in his lab this year. He also received funds from ASRA (~$91K), the University of Alberta (~$80K) and in-kind contributions (~$80K) from industry.

PUBLICATIONS

PUBLICATIONS

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PRESENTATIONS

INVITED TALKS GIVEN BY WOLKOW

Intoduction to nanoscience, Canadian Physics Olympiad (for high school students), Univeristy of Alberta, Edmonton, 30 April 2005

A lay accessible description of nanotechnology, Medical Physics section of the Grand Oncology Rounds, Cross Cancer Institute, Edmonton, 19 April 2005

Hybrid Molecule-Silicon Nanoscience: Laying a foundation for Molecular Devices, Pacific Centre for Advanced Materials and Microstructures annual meeting, Vancouver, 4 Dec 2004.

Hybrid Molecule-Silicon Nanoscience: Laying a foundation for Molecular Devices, Physics Department, McGill University, 9 Sept. 2004

Hybrid Molecule-Silicon Nanoscience: Laying a foundation for Molecular Devices, NASA Institute for Nanoelectronics and Computing, 2nd Annual Workshop on Molecular Conduction, Northwestern University on July 8-10, 2004.

Hybrid Molecule-Silicon Nanoscience: Laying a foundation for Molecular Devices, Electronic Structure and Simulations of Nanostructures, towards an understanding of physical, chemical and biological processes, Jyvaskyla, Finland, June 2004.

Three Lecture Series, ICTP Spring College on Science at the Nanoscale, Trieste, Italy, May 2004

Keynote Speaker, 29th annual APICS/CIC Student Chemistry Conference, St Mary's University, Halifax, May 13-15, 2004.

Hybrid Molecule-Silicon Nanoscience: Laying a foundation for Molecular Devices, Seminar, Dalhousie University, 14 May, 2004

CONTRIBUTED TALKS BY DILABIO

"Carbodiimide Insertions into Aluminum Compounds." Canadian Society for Chemistry 87th Canadian Chemistry Conference, London, Ontario, Canada, May 29-June1, 2004.

"Reaction of Semiquinone Radicals with Oxygen: Explaining the Antioxidant Efficacy of Hydroquinones.", 9th International Symposium on Organic Free Radicals, Porto Vecchio, Corsica, June 6-11, 2004.

"Computational Modeling of Processes Leading to Self-Directed Assembly on Silicon Surfaces: Progress Toward Hybrid Organic-Silicon Nanostructure Formation", 15th Canadian Symposium on Theoretical Chemistry, Sainte-Adele, Quebec, Canada, July 10-14, 2004.

"Self-Directed Assembly of Hybrid Organic-Silicon Nanostructures: Experimental and Computational Opportunities for Graduate Students", iSmack Conference, Department of Physics, University of Alberta, Sept. 10, 2004.

"Effective Computational Modeling of Large Chemical Systems Using Quantum Capping Potentials", 32nd Ontario-Quebec Physical Organic Mini-Symposia, Queen's University, Kingston, Ontario, Canada, Nov. 12-14, 2004.

INVITED TALKS BY DILABIO

"Computational and STM Studies of Chemical Processes on Silicon Surfaces: Progress Toward Controlled Hybrid Organic-Silicon Nanostructure Formation." Symposium: 50 Years of Free Radical Chemistry at NRC. September, 2004.

"Computational and STM Studies of Chemical Processes on Silicon Surfaces: Progress Toward Controlled Hybrid Organic-Silicon Nanostructure Formation." Department of Chemistry, Carleton University, Ottawa, ON. September, 2004.

"Practical Aspects of Quantum Mechanical Prediction of Thermochemical Properties." National Centre for Upgrading Technologies, Devon, AB. March, 2005.

"Novel Chain-Breaking Antioxidants based on Pyridinol and Pyrimidinol: From in silico Design to in vitro Testing." Department of Chemistry, University of Alberta, Edmonton, AB. March, 2005.

CONTRIBUTED TALK BY PITTERS

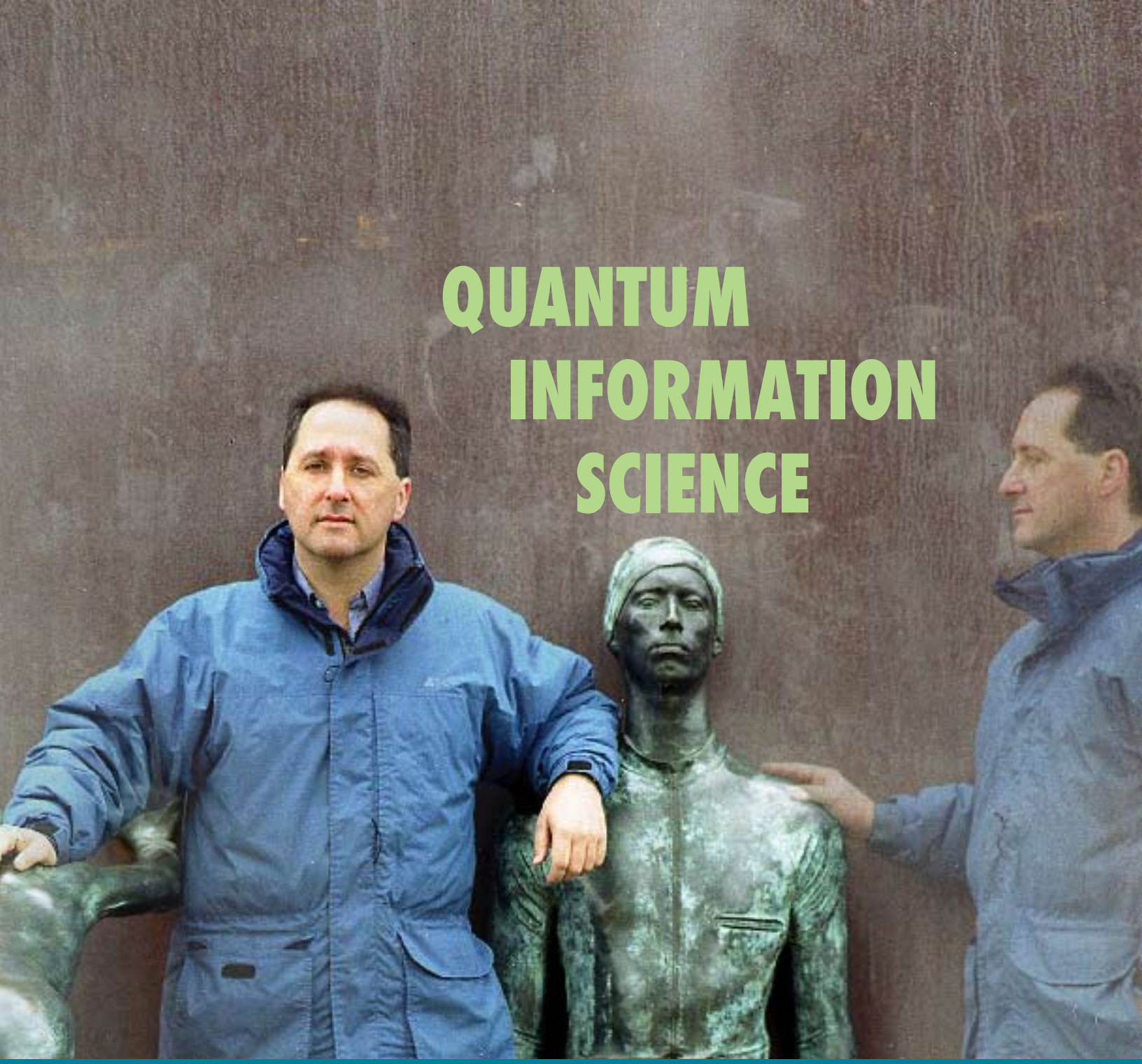
"Protection-Deprotection Chemistry to Control Styrene Self-Directed Line Growth on Hydrogen-Terminated Si(100)". American Chemical Society. San Diego, California. March 2005.

"Self Directed Assembly of Hybrid Organic-Silicon Nanostructures". iSMACK Conference. Department of Physics. University of Alberta. Edmonton, Alberta. September, 2004. (poster presentation)

INVITED TALKS BY PITTERS

"Controlled Molecular Adsorption on Silicon. Laying a Foundation for Molecular Devices". Nanoforum Canada. Edmonton, Alberta. June, 2004.

"Nanotechnology and the Scanning Tunneling Microscope" Strathcona Advanced Placement Program. Lecture given to high school students in order to introduce nanotechnology. Edmonton, Alberta. April 2004.



QUANTUM INFORMATION SCIENCE

The Institute for Quantum Information Science regards education and training of highly qualified personnel as equal in importance to research. The undergraduate quantum mechanics course Physics 443 has been modernized to include QIS, and two Physics graduate courses have been created ("Implementations of Quantum Information" and "Quantum Optics") to complement existing Computer Science courses on QIS.

BARRY SANDERS

iCORE Professor and Director of the Institute for Quantum Information Science at the University of Calgary
www.iqis.org

Quantum information science (QIS) is concerned with revolutionary implications of quantum devices and systems to information and communication science and technology. Although the field is in an embryonic stage, remarkable achievements so far have included the introduction of quantum cryptography — which can provide unconditionally secure public key generation, efficient period-finding algorithms for a quantum computer — which render general public encryption schemes insecure against quantum attacks, and quantum searches — which are provably faster than any classical search. The University of Calgary is a leader in QIS through the research activities of computer scientists and theoretical and experimental physicists within the Institute for Quantum Information Science. Calgary's focus is on the full spectrum of QIS research, from foundations to algorithms to experimental implementations.

EXECUTIVE SUMMARY

The Institute for Quantum Information Science (IQIS) is the culmination of successful efforts to establish the University of Calgary as one of the few locations worldwide with a concerted effort into theoretical and experimental studies of QIS. This was followed by the establishment of a Tier II Canada Research Chair in Quantum Computing in the Department of Computer Science and by the establishment of iCORE Professorship of QIS and nomination of a the Tier II Canada Research Chair in Quantum Optics in 2004, both in the Department of Physics and Astronomy. These initiatives provide IQIS with its three planks: computer science, theoretical physics, and experimental physics. With support from General Dynamics Canada, an Industrial Research Chair in Quantum Cryptography will be established in 2006. This appointment will expand QIS activities into practical applications with an industrial partner.

The Institute has rapidly expanded to seven faculty team members and a senior research fellow (who is also an adjunct professor in the Department of Physics and Astronomy), two postdoctoral research fellows (supported by external grants), four postdoctoral research associates (supported by various research grants), ten PhD and five MSc students in two departments, and two research assistants.

IQIS research activities can be categorized as:

- Foundations including measurement theory, nonlocality and distinguishability, and mathematical methods
- Resources, including coherence, entanglement, and squeezing
- Enabling technologies, including nonclassical light sources, optical nonlinearities, and detectors
- Implementations, including quantum fingerprinting, shared quantum states, and remote preparation of entanglement
- Algorithms and complexity, including new quantum complexity classes and algorithmic primitives such as quantum walks
- miscellaneous research such as photonic crystals and ultracold atoms

All core IQIS research fits into the first five categories. In addition to research endeavours, IQIS has expanded graduate-level teaching in QIS, modernized the undergraduate quantum mechanics class, introduced a quantum information reading club, and created qviz.org for visualization research and products concerning QIS.

IQIS has grown quickly into a highly respected, large research hub with activities spanning the broad spectrum of QIS. Significant advances in theory and experiment, especially in the areas of implementations and algorithms, have been achieved as well as

educational initiatives including new courses and a quantum visualization project.

RESEARCH PROGRAM OVERVIEW

The goals of the iCORE program in QIS at the University of Calgary are as follows: to establish leadership in both theoretical and experimental QIS research, including research on new quantum information processing algorithms and protocols, research on experimental realizations of a quantum computer, and development of new physical implementations for quantum computing paradigms; to educate and train highly qualified personnel for QIS and allied disciplines; to create a multidisciplinary community of researchers collaborating on the key problems in QIS; and to identify promising research areas that will lead to valuable intellectual property and to conduct research into these areas.

To establish leadership in theoretical and experimental QIS research the research team has been enhanced by the appointment of Dr A. Lvovsky, as an Associate Professor in the Department of Physics and Astronomy with a nomination for a Tier II Canada Research Chair in Quantum Optics. Also, Dr B. Sanders has been recognized for his achievements by his election as a Fellow of the Optical Society of America and as a Fellow of the Institute of Physics (U.K.), and appointed as an associate of the Canadian Institute for Advanced Research Quantum Information Program, appointed as a founding member of the Advisory Board for the newly established American Physical Society Topical Group on Quantum Information Science.

The University of Calgary's leadership in QIS is also evident in the following research indicators: 14 invited conference and workshop presentations and 6 external colloquia, 12 mentions in the Calgary media and 20 mentions by other national and international media. Faculty members have been on 6 organizing and program committees of national and international conferences. A partnership with General Dynamics Canada has been established. This corporate partner is supporting QIS research via funding through the National Centre of Excellence for Mathematics of Information Technology and Complex System and by supporting one of their senior employees as he undertakes a part-time PhD in IQIS. Canada's Communications Security Establishment and a US Government agency have also sponsored research in Calgary.

IQIS regards education and training of highly qualified personnel as equal in importance to research. The undergraduate quantum mechanics course Physics 443 has been modernized to include QIS, and two Physics graduate courses have been created ("Implementations of Quantum Information" and "Quantum Optics") to complement existing Computer Science courses on QIS. Also collaboration with the Banff New Media Institute has created educational and informative visualizations on quantum information, which can be viewed at www.qviz.org.

The establishment of IQIS creates the foundation for our multidisciplinary community, although the lack of quality space for interactions and for co-location is a limiting factor. Collaborative work between computer scientists and theoretical and experimental physicists has commenced on quantum walks, quantum simulations of Hamiltonian systems, and quantum fingerprinting. A weekly IQIS Seminar series and weekly Reading Club sessions are well attended.

Major collaborative research efforts have commenced in quantum fingerprinting, quantum memory, and distinguishability. Through collaboration between theoretical and experimental physicists and computer scientists, the challenge of single-qubit fingerprinting has been solved and tested experimentally. Headway is being made into multi-qubit fingerprinting, which will be necessary for verifying the validity of quantum states in some applications. Quantum memory will be realized experimentally in Calgary as a joint effort between experimental and theoretical physics; through electromagnetically-induced transparency in a Rubidium gas. A third major research area is a collaboration involving computer science and theoretical physics on nonlocality and indistinguishability of states, which is at the heart of measurement issues in quantum information protocols.

RESEARCH PROJECTS

Foundations

Geometric phase is important for a class of proposed quantum computers as it is especially robust against certain kinds of errors. Much of the theory applies to closed systems, but closed systems are (by definition) non-interacting with the external world, including measuring devices, control systems, and sources. The theory needs to be connected with the practical world, and our researchers have obtained new results on how to consistently treat the geometric phase in open systems. In addition to advancing the theory of geometric phase, a tangential result has been the iconoclastic realization that the venerable adiabatic theorem is insufficient to justify the standard assumption of its wide applicability. Our results have engendered an international effort to tighten this theorem. In a study of mathematical methods for open systems, we have developed a theory of super-operator norms.

Quantum measurements are critical to extracting maximal information from quantum systems and also for quantum control. In collaboration with Macquarie University and the University of New Mexico, we have developed a generic theory of continuous quantum measurements that will be applied to atomic experiments. In particular we applied this theory to quantum chaotic transitions and successfully elucidated the puzzling quantum-to-classical transition.

Resources

Coherence is a critical resource for quantum information processing; essential for constructive interference of quantum information, and avoiding the loss of coherence (decoherence). In collaboration with Masaryk University (Czech Republic) and Massachusetts Institute of Technology, we have formulated a theory of coherence for fermionic systems, which is especially useful for analyzing limitations of electron systems. Progress has been made in identifying strategies for avoiding decoherence in atomic systems, in collaboration with long-term visiting students from Macquarie University and University of California at Berkeley. Progress is also being made on studies of super-radiance and sub-radiance, which are manifestations of collective atomic effects that are related to suppression of decoherence in atomic systems, in collaboration with the Universities of Oregon and Auckland.

We now recognize the importance of nonlocality as a resource for quantum information processing, which is different from entanglement and yet is essential for protocols. Specifically, we are investigating the roles of nonlocality and indistinguishability of quantum states, and, in collaboration with the California Institute of Technology, we have analyzed nonlocality in the context of game theory. Studies of entanglement as a resource continue to be important, and, in collaboration with the University of Queensland, we have constructed equivalences between squeezing and entanglement as well as quantified the entanglement capacities of two-qubit gates. We have also analyzed entanglement distillation and, in collaboration with Zhejiang University, constructed theories for entanglement of indistinguishable particles. From our foundation work on quantum measurement of quantum chaotic systems, we have discovered that quantum chaotic systems yield rapid entanglement generation, which may provide an efficient entanglement generator.

Enabling

As near-future applications of QIS are likely to be optical, we have concentrated our efforts in "enabling technology" in the quantum optics arena. Specifically we have focused on improving single photon sources, performing homodyne tomography, and creating nonlinear gates. In collaboration with researchers at Imperial College and the Universities of Waterloo and Queensland, we have studied interferometric post-processing of outputs from single-photon sources to ascertain whether such schemes can enhance the efficiency for producing single photons. So far we have only bad news: no-go theorems telling us when improvement cannot be attained, but these theorems provide intuition that is helpful for seeking strategies for improving single photon sources.

Barry Sanders and some research team members at the 2005 Banff Informatics Summit

Optical nonlinearities are important for optical quantum information processing. Although much recent effort has been dedicated to linear optical implementations, optical nonlinearities may be essential for introducing quantum memory and deterministic logic gates into circuits. We believe that electromagnetically induced transparency in atomic gases, which can halt light, presents an excellent prospect for nonlinear gates and optical memory, and we are planning such Rubidium vapour experiments in Calgary.

In other work concerned with enabling technologies for QIS, we have developed a method for detecting atomic entanglement by velocity-selective coherent population trapping and constructed optimal methods for reconstructing quantum states, including photonic qubits, using maximum likelihood methods. The effort in the enabling technology strand of QIS research continues to address technological requirements for optical implementations of QIS, especially on nonlinear optical gates and memory and on single photon sources.

Implementations

The goal of the implementations research program is to transform QIS concepts into implementations in atomic and photonic systems. One such success has been quantum state sharing, demonstrated experimentally in collaboration with Masaryk University, the Australian National University, and the California Institute of Technology. This protocol will be important for distributing quantum states to multiple untrustworthy parties in a network as well as for protecting states. Our other major success has been quantum fingerprinting, which was adapted for single-qubit realization through collaboration between all three planks of IQIS: computer science and theoretical and experimental physics. Our theoretical and experimental successes in this area lay the foundation for few-qubit applications, which may be applied to quantum authentication.

Another concern has been remote preparation of entangled states in a quantum network with only one supplier of entanglement. In this scenario, production of entangled states is regarded as expensive so we allow just one entanglement supplier. The goal is to distribute entanglement and prepare bipartite states on demand. Currently the work, conducted in collaboration with the University of Alberta and the University of California at San Diego, is mathematical but should become applicable to certain proposed distributed quantum computers.

Algorithms and Complexity

The University of Calgary has played an important role in the study of quantum walks, which is an important primitive for some quantum algorithms. In the past year, collaborative work between computer science and physics, with the University of Queensland, has led to new, efficient techniques for simulating quantum walks on graphs. These results have suggested general speed-ups for simulating physical systems. Quantum walks with absorbing boundaries have been addressed in collaboration with University of Wisconsin at Madison. In collaboration with Imperial College, identifying the quantum-to-classical transition has elucidated the quantum essence of walks.

Another major effort of study is in the area of complexity. Specifically, quantum query complexity is being investigated for problems, especially the important hidden subgroup problem (at the heart of quantum attacks on classical cryptography), in collaboration with Los Alamos National Laboratories. New headway has been made in the area of quantum query complexity with competing provers.

Barry Sanders at the iCORE Quantum Information Science launch

OBJECTIVES FOR NEXT YEAR

QIS is looking forward to exciting prospects in 2005-06 as the Institute expands. Goals for the Institute include a transition to full institute status, to build on the partnership with General Dynamics Canada, which will lead to the establishment of an industrial chair in quantum cryptography, and to join in a network with other Canadian QIS Centres and Institutes. The charter for the Institute should be completed in 2005 and a governing board established. The QViz (Quantum Visualization) project will be selling informative and educational products, which will create a

self-sustaining effort to create new and much-needed visualization products to inform students, the public, and decision-makers. To enhance the QIS experience for IQIS members and Science and Engineering faculty and students at the University of Calgary, IQIS will launch a monthly distinguished colloquium series with leading international QIS speakers.

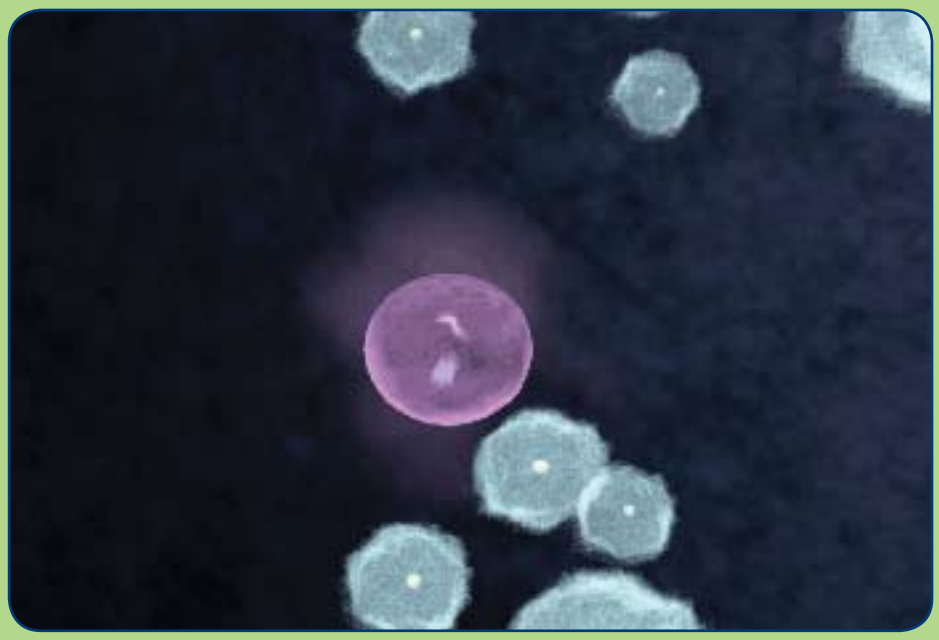
In research, the quantum fingerprinting effort is set to grow: the single-qubit fingerprinting research this year will engender theoretical few-qubit fingerprinting studies in the coming year plus proposals for new experiments. Storage of quantum fingerprints will be important, and the quantum memory project, based on electromagnetically-induced transparency, should be operational by 2005, with the capability to store or slow down some nonclassical states of light and fully characterize their properties, using homodyne detection. We will explore applications of quantum fingerprinting to authentication and state protection.

A full treatment of nonlocality and distinguishability is planned by 2005 where applications to measuring states, including the context of efficient quantum fingerprinting, will be studied. In addition, a careful analysis of entanglement distribution, quantum teleportation, and state sharing, all assuming imperfect gates, will be undertaken with the goal of assessing the feasibility of schemes for long-distance quantum communication (beyond the limit where quantum coherence breaks down). The establishment of shared reference frames (for example, alignment and synchronization) beyond distant quantum systems has become an important topic, and we plan to investigate its role in long-distance quantum communication and compromises to security due to the need to replenish reference frames. Our treatment will be sufficiently generic to include both boson and fermion systems.

Another key area of research will be a quantum algorithm for simulating dynamics of quantum systems and quantum graphs. We will identify optimization conditions for such simulations. Also we plan to tighten the adiabatic theorem and its application. Both these efforts are important for near-term quantum computation. Simulating physical systems is likely to be the first application of quantum computers, given that such devices will have few qubits and therefore are not so useful for period-finding. We will also be working on continuous variable quantum information, which seems to offer promising possibilities for fast quantum key distribution but suffers from a lack of security proofs. In addition to our quantum cryptography work in this area, we are also studying continuous variable quantum cryptanalyis by constructing a new quantum algorithm to find periods based on the Deutsch-Jozsa algorithm but in the context of continuous variables.

Our educational objectives are to launch QViz as a self-funding project, increase our number of graduate students concomitantly with boosting quality of students, increase the number of postdoctoral researchers, and improve our graduate course offerings. In the past year, we have hosted exchange students; this coming year will see our students being hosted by partner institutions. Our goal is to create an educational environment in IQIS equal to the outstanding research environment.

Visualization of correlated photons



RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

TEAM LEADER	ROLE/TOPIC/AWARDS
Dr Barry Sanders	iCORE Professor of QIS
	Elected Fellow of the Optical Society of America Elected Fellow of the Institute of Physics (UK) Appointed Associate of CIAR Program on Quantum Information Processing

Faculty Members

	ROLE/TOPIC/AWARDS
Dr Richard Cleve	University Professor, Computer Science
Dr David Feder	Assistant Professor, Physics and Astronomy
Dr David Hobill	Associate Professor, Physics and Astronomy
Dr Peter Høyer	Assistant Professor, Computer Science
	Best European Association for Theoretical Computer Science paper (Track A) at International Colloquium on Automata, Languages, and Programming
Dr Alexander Lvovsky	Associate Professor, Physics and Astronomy
Dr John Watrous	CRC II of Quantum Computing

Research Associates

	ROLE/TOPIC/AWARDS
Dr Somshubhro Bandyopadhyay	Post-Doctoral Research Associate Theory of Entanglement
Dr Shohini Ghose	Post-Doctoral Research Fellow QI Implementations, Quantum Measurement
Dr Hartmut Klauck	Post-Doctoral Research Associate Quantum Complexity
Dr Karl-Peter Marzlin	Senior Research Associate and Adjunct Professor QI Implementation, Coherence In Atomic Media
Dr Mehdi Mhalla	Post-Doctoral Research Associate Quantum Computing
Dr Hein Röhrig	Post-Doctoral Research Associate Quantum Algorithms
Dr Andrew Scott	Post-Doctoral Research Associate Quantum Chaos
Dr Jonathan Walgate	Post-Doctoral Research Fellow Extracting Information from Quantum Systems

PhD Students

	ROLE/TOPIC/AWARDS
Mark Adcock	Continuous Variable Quantum Networks
Jürgen Appel	Exchange of Quantum Information Between Light and Atomic Ensembles

	ROLE/TOPIC/AWARDS
Sergey Babichev	Quantum Technology of Light
Eden Figueroa	Quantum Source of Light for Experiments with Atoms
Dmitry Gavinsky	Quantum Algorithms
Heath Gerhardt	Continuous-time Quantum Walks on the Symmetric Group
Thomas Harmon	Cavity Quantum Electrodynamics with Ions
Yeongyoon Kim	Sharing Entangled Quantum Secrets
Iyad Mahmoud	Collective Effects In Dense Gases
Alexis Morris	Topological Quantum Computing
Xue Song Qi	Entanglement in Cavity Quantum Electrodynamics
Zeng Bin Wang	Electromagnetic-Induced Transparency with Single Photons

MSc Students

	ROLE/TOPIC/AWARDS
Graeme Ahokas	Approximate Quantum Fourier Transforms and Hamiltonian Simulation
Richard Cannings	On the Security of the BB84 Quantum Key Distribution Protocol
Niel de Beaudrap	One Qubit Fingerprinting Schemes
Mike Garrett	To be decided
Gus Gutoski	Quantum Interactive Proofs with Competing Provers
Kris Luttmer	Complexity of Separability Testing
Jibran Rashid	Bounds on Quantum Non-locality
Stuart van der Lee	Quantum Walks on Optical Lattices
Hongchao Zhang	Quantum Computing

Undergraduate Students

	ROLE/TOPIC/AWARDS
Sharon Fast	Entangled Current States for Ultra-Cold Atoms
Phil Vorvis	Electromagnetic-Induced Transparency in BEC

Administrative Staff

NAME	TITLE
Catherine Avramenko	Administrator, IQIS
Roberta Curnew	Administrator, IQIS
Lance Hanlen	Webmaster
Jill Kowalchuk	Report Officer
Lisa Kowalko	Administrative Assistant (Temp), PHAS QIS Group

Visitors

IQIS brings together top researchers in the world in order to further the development of the field of quantum information science through a focused, multi-disciplinary effort.

	STATUS	HOME INSTITUTION
Anton Zeilinger	Academic	Institut für Experimentalphysik, Universität Wien
Frank Vewinger	PhD Student	University of Kaiserslautern
Safa Jami	PhD Student	Ferdowsi University of Mashhad
Bob Gelfond	Industrial	CEO, MagiQ Technologies
Leonard Schulman	Academic	California Institute of Technology
Raymond Laflamme	Academic	Director, Institute for Quantum Computing, University of Waterloo
Daniel Gottesman	Academic	Perimeter Institute
Chip Elliott	Industrial	BBN Technologies
Steve Woolgar	Academic	University of Oxford
Peter Brooke	PhD Student	Macquarie University
Paul C. Haljan	Academic	University of Michigan
Nathan Wiebe	MSc Student	Simon Fraser University
Alex Brown	Academic	University of Alberta
Hilary Carteret	Academic	Université de Montréal
Marie Ericsson	Post-Doctoral Fellow	University of Cambridge
Hirotada Kobayashi	Academic	Japan Science and Technology Agency
Mario Szegedy	Academic	Rutgers University
Raisa Karasik	PhD Student	University of California, Berkeley
Philipp Schneeweiß	MSc Student	University of Dresden
Viv Kendon	Academic	Imperial College
Suneeta Vardarajan	Post-Doctoral Fellow	University of Alberta
Gilad Gour	Killam Post-Doctoral Fellow	University of Alberta
Tom Stace	Fujitsu Post-Doctoral Fellow	University of Cambridge
René Stock	PhD Student	University of New Mexico
Dominic Berry	Post-Doctoral Fellow	Macquarie University
Tomáš Tyc	Academic	Masaryk University
Prashant Singh	MSc Student	Indian Institute of Information Technology and Management
Tien Kieu	Academic	Swinburne University
Alex Lvovsky	Academic	University of Konstanz

COLLABORATIONS

PARTICIPANTS	NATURE OF COLLABORATION
PROVINCIAL	
University of Alberta	Mathematical physics study of entanglement distribution
NATIONAL	
University of Waterloo	Strategic research on photon sources and quantum algorithms
INTERNATIONAL	
Australian National University	Experimental collaboration on sharing quantum states
California Institute of Technology	Research on experimental quantum state sharing, also on nonlocality "games"
Centre National de la Recherche Scientifique, Grenoble	Research on quantum complexity
Hong Kong Baptist University	Research on quantum chaos
Imperial College of Science, Technology and Medicine	Research on quantum walks and single photon sources
Los Alamos National Laboratory	Research on quantum complexity
Macquarie University	Research on quantum chaos, quantum algorithms, and entanglement
Massachusetts Institute of Technology	Research on fermionic coherence
The University of Queensland	Research on single photon sources
University of Auckland	Research on superradiance
University of Bristol	Research on nonlocality
University of California at Berkeley	Mathematical physics research on decoherence free spaces in atomic systems
University of California at San Diego	Mathematical physics research on distributing entanglement
University of Konstanz	Research on experimental homodyne tomography and theory of atomic gap solitons
University of New Mexico	Research on quantum chaos and quantum measurement
University of Oregon	Research on superradiance
University of Wisconsin, Madison	Research on quantum walks
Zhejiang University	Research on quantum chaos and on entanglement
INDUSTRIAL	
Communications Security Establishment	Research on quantum complexity and quantum algorithms
General Dynamics Canada	Research on quantum cryptography and quantum algorithms
US Government Agency	Research on quantum complexity

FUNDING

This year Barry Sanders received federal funding from NSERC (~$324K), CIAR ($75K), provincial funding from AIF ($86K) and a grant from iCORE for $600K. Industry contributions totaled ~$219K and he also received funding from the University of Calgary (~$806K) and a combined amount (~$92K) from other contributors including MITACS and PIMS.

PUBLICATIONS

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S. Ghose and B. C. Sanders, "Entanglement dynamics in chaotic systems", *Physical Review A*, vol. 70, no. 6, Dec. 2004, pp. 062315-1 to 062315-5.

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I. Kamleitner, J. D. Cresser and B. C. Sanders, "Geometric phase for an adiabatically evolving open quantum system", *Physical Review A*, vol. 70, no. 4, Oct. 2004, pp. 044103-1 to 044103-4.

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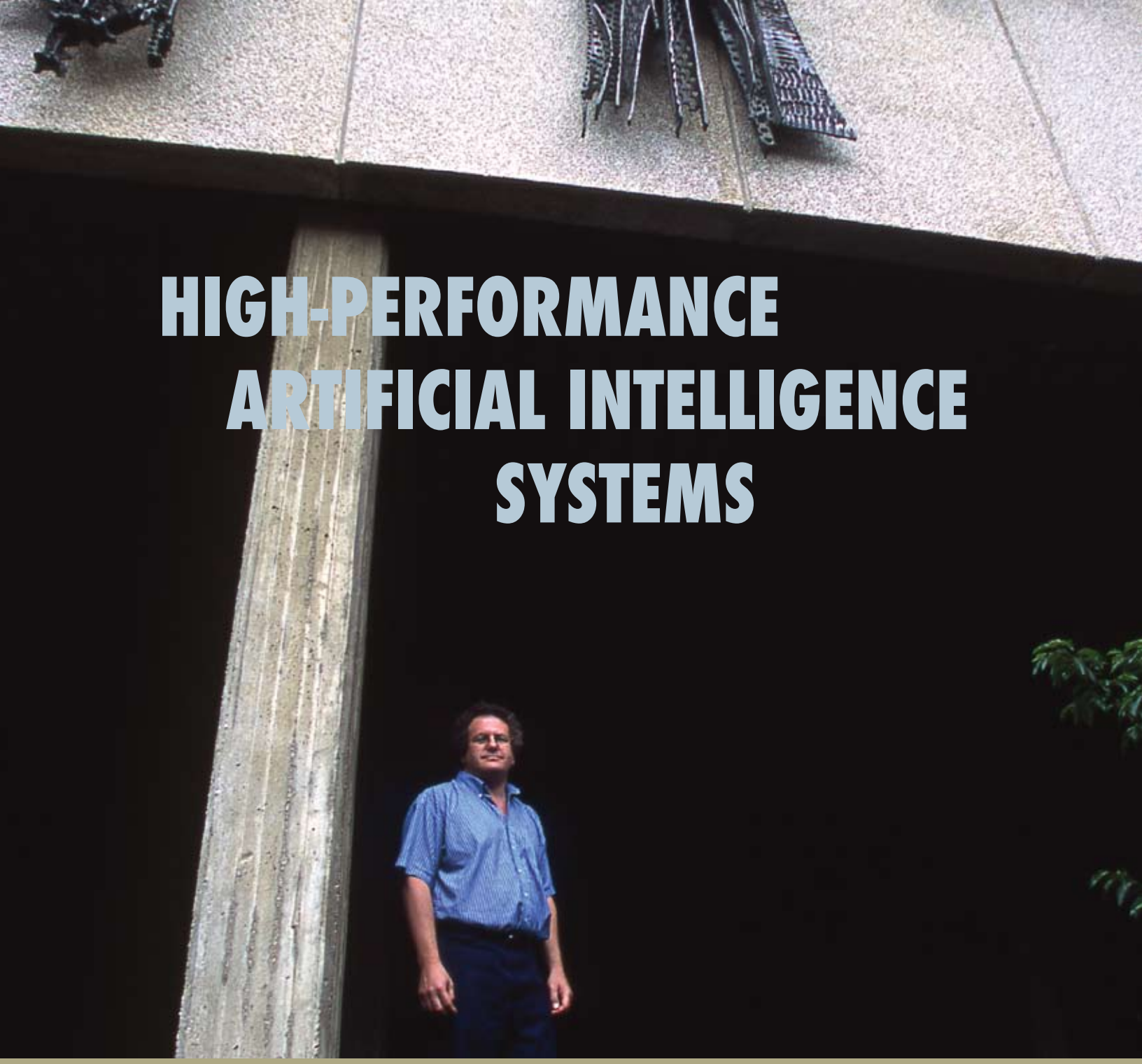

HIGH-PERFORMANCE ARTIFICIAL INTELLIGENCE SYSTEMS

Fundamental problems in artificial intelligence are being investigated in the context of computer programs that play chess, checkers, Go, and poker. Many of our game-playing programs have achieved a high level of performance and have challenged the best human players in the world.

JONATHAN SCHAEFFER

iCORE Chair
Computing Science, University of Alberta
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The High-Performance Artificial Intelligence Systems research group specializes in artificial intelligence research – investigating new technologies for creating "intelligent" behaviour in a computer.

EXECUTIVE SUMMARY

Our team's research spans many areas of artificial intelligence — including search, machine learning, and heuristic knowledge. Historically we have used games to demonstrate the ideas. Fundamental problems in artificial intelligence are being investigated in the context of computer programs that play chess, checkers, Go, and poker. Many of our game-playing programs have achieved a high level of performance and have challenged the best human players in the world via the web. Current work applies our technology to the challenges of commercial games.

RESEARCH GOALS AND OBJECTIVES

Our group has built an international reputation based on our artificial intelligence (AI) research, using games as an experimental test-bed for this work. Because the research challenges from the classic board and card games are limited (the games of poker and Go being notable exceptions), since 1999, we have been slowly moving our research efforts towards addressing the challenges of the commercial games industry. This represents an excellent opportunity for us, since the use of AI in this industry is still in its early adopter stage.

In the past year we have strengthened our international reputation in the commercial games industry. Three major games companies have made big commitments to support our group's research. We have become the largest research group in this area and are recognized academically as being leading edge. However, there is a large gap between academic research and industry expectations. The commercial games industry in particular is heavily performance oriented. They need real-time solutions that use little CPU and memory. Few AI efforts address real-time constraints, but this area is one of our group's strengths. We are not developing industrial strength solutions for our partners, but we are building proof-of-concept demonstrations to show that our technology can meet the stringent industry demands.

Our group continues to build on its past success in AI. Most notable is the poker project, which is addressing the hard AI problems of reasoning with imperfect and incomplete information. In the last quarter of the iCORE year, we finally broke through and moved our technology up to the next level. We look forward to an exciting year ahead, with good prospects for a man–machine match for poker supremacy. The program has been commercialized (http://www.poker-academy.com) and is receiving excellent reviews.

The long-term objective of our work is to enhance our understanding of search, knowledge and their interactions, working on developing high-performance search algorithms. Unlike most research groups, we build complete AI systems, addressing all the issues needed to achieve high performance.

RESEARCH PROJECTS

Our group has many research projects under way. In this section, the major efforts are highlighted.

Commercial Games Research

In the past, computer graphics were the major technological differentiator between competing game products. Now, the realism of the graphics has increased consumer demand for realism in the game

characters. The commercial games industry now recognizes that AI has become a major consumer consideration in assessing the quality of a product. Unfortunately, the games industry has few AI experts and almost no resources are devoted to research. This gives university researchers an opportunity to have a major impact in new technology development. In academia, the University of Alberta has the world's largest research group working in this area.

Our first major research thrust is in AI scripting. Character behaviours in games are usually defined using scripts. However, the result is complex software that is hard to maintain. Further, the resulting performance of the characters is disappointing because the characters will only precisely do what has been scripted, and typically this is a very small set of behaviours. We have been developing a tool that allows for the rapid construction of complex character behaviours. The tool, called ScriptEase, is based on having a rich set of pre-defined patterns, for character behaviours, conversations, situations, and plot, that the user can select and then customize to their needs. This work is novel and, because of our extensive experience with patterns, gives us a competitive edge for developing the next generation of scripting technology. Our tool has been used to build complex stories in a very short time, as evidenced by experiments we have done with high school and novice game players. We have brought ScriptEase into the classroom, making it part of an Edmonton high school's grade 10 curriculum. Creating realistic characters has many industrial applications including training programs, web interfaces, and other forms of interactive entertainment.

Jonathan Schaeffer

ScriptEase was made publicly available (in November, 2003; http://www.cs.ualberta.ca/~scripting), and has been downloaded over 10,000 times.

The second major research topic is pathfinding. For many computer games, the "simple" task of having a character find a path from their current position to a goal is a time-critical, CPU-intensive function. This is an instance of a problem domain called single-agent search, but in this case is restricted to a two-dimensional grid (with the intent of moving to three dimensions). This technology is applicable to a wider domain of applications, including robot planning. We developed new algorithms for grid-based pathfinding that are being used by BioWare and by Relic Entertainment. The current work is on pathfinding for real-time strategy games, where, potentially, hundreds of characters are moving independently throughout a virtual world.

The third research objective is to apply machine learning to games. Game companies are reluctant to ship games that learn in response to the user's interactions. The reason for this is that it is difficult to control the learning, and a player can contrive to have a program learn poor behaviour. Also, conventional learning algorithms are either too slow, or learn too slowly. We have developed new learning algorithms for Electronic Arts FIFA soccer game that are being evaluated by the company for possible inclusion in their next product.

Classic Games

Traditional games research has concentrated on two-player games of perfect information — where the opponents are not hiding anything. Poker is very challenging because of hidden information, multiple players, and deception. These dimensions significantly complicate the problem domain, making it an application domain that better represents the complexities of intelligence in real life. For example, poker is a model for economic game theory as well as business negotiations and Internet auctions.

For over a decade we have been developing new technologies for dealing with imperfect information. We have applied the notion of Nash equilibriums to build a pseudo-optimal two-player poker program (an optimal program is too computationally expensive to build right now). This program achieved international success by narrowly losing a match to a world-class player in January 2003. We have improved this program, and have developed new approaches to tackling the poker "problem". We continue to look for a sponsor for a man-machine poker match.

For over a decade we have been working on solving the game of checkers. We want to construct a program

that will never lose, assuming checkers is a draw with perfect play, as seems likely. The game has a search space of roughly 5×10^{20}. Although the final result—solving checkers—is not particularly exciting from the scientific point of view, the technology and tools developed to solve such a large computational problem are relevant to a wide audience. In 2005, we achieved a milestone in our quest; one opening, the 'White Doctor', has been solved. With perfect play, it is a draw. There are 173 more checkers openings, but we only need to solve a minimum of 50 of them before we might be able to determine the final result of checkers.

Another major initiative is with the Oriental game of Go. This game is especially interesting because, unlike chess, search is ineffective. Success in the game depends on using complex interacting knowledge. Martin Müller has built up a team of six people working on computer Go. They have developed two of the strongest Go programs in the world.

Applications of Game Technologies

Many of our search-based research contributions are applicable to the field of AI planning systems. For the past two years we have been developing new technologies for planning systems. Our technology takes a planning problem domain (for example, a robot having to plan how to restock inventory) and decomposes it into a global problem (what has to be done) and a series of local problems (stocking individual items). The result is a system that can come up with workable plans considerably faster than conventional approaches. This has been tested on a variety of real-world domains including pathfinding, aircraft landing schedules, pipeline layouts, and transportation schedules. We enhanced Joerg Hoffman's FF planner with our new research results. Our program, MACRO-FF, won three of the seven competitions it entered in the biennial International Planning Competition. Our new research results show a massive improvement over the program that entered the competition.

In a new project we are using search algorithms to automate the layout of sanitary and storm sewers in housing subdivisions. We are working closely with Simaan Abou-Rizaak (Civil Engineering, University of Alberta) and civil engineering companies. We have our first results: the program can compete with the best human engineers in layout quality, but at a fraction of the time and less cost of doing it manually.

WestGrid

Although this is not a direct research contribution, in many ways the WestGrid project may have the most long-term impact. WestGrid is a partnership of seven Alberta and British Columbia institutions working to bring world-class high-performance computing resources to Western Canada. The partners are the University of Alberta, University of British Columbia, University of Calgary, University of Lethbridge, Simon Fraser University, TRIUMF, and The Banff Centre. This project was successful at achieving roughly $50 million of funding from the Canada Foundation for Innovation, the province of Alberta, the province of British Columbia, computer vendors, and the member institutions. The five co-principal investigators for the project are Jonathan Borwein (Simon Fraser Uni-

Jonathan Schaeffer and some research team members in Edmonton, 2004

versity, now of Dalhousie University), Grenfell Patey (University of British Columbia), Jonathan Schaeffer (University of Alberta), Brian Unger (University of Calgary), and Michel Vetterli (TRIUMF and Simon Fraser University). Although our research will benefit in only small ways from this infrastructure, the impact on the research productivity of Alberta and British Columbia researchers will be immense. There will be major benefits to researchers in areas diverse as biology, chemistry, physics, engineering, medicine, and the social sciences.

WestGrid II, which encompasses all major research institutions in Alberta, British Columbia, Manitoba and Saskatchewan, is gearing up for the next Canada Foundation for Innovation competition.

Objectives for the Next Year

Our research will progress towards the vision outlined above. A list of key objectives to strive for in 2005-2006 includes:

- A man-machine match in poker against one of the best players in the world. Win, lose or draw, this would be a major historic milestone.
- Solving more checkers openings
- Building our own high-performance planner from scratch (removing the dependency on FF), with a view towards competing in the 2006 International Planning Competition
- Enhancing the capabilities of ScriptEase and make a more ambitious foray into using it in education.
- Completing the sewer layout program, expanding its capabilities for more complex layouts, and engaging an industrial partner
- Strengthening our ties with the commercial games industry
- Partnering so our commercial games technology will appear in more commercial products

RESEARCH TEAM

Faculty Team Members

The table below lists the faculty members involved in this research group and the percentage of their time committed to the project.

NAME	TITLE	PERCENT
Michael Bowling	Assistant Professor	30
Vadim Bulitko	Assistant Professor	50
Michael Buro	Associate Professor	100
Mike Carbonaro	Associate Professor (in Education)	25
Ryan Hayward	Professor	25
Rob Holte	Professor	50
Paul Lu	Assistant Professor	10
Martin Müller	Associate Professor	100
Jonathan Schaeffer	Professor	100
Duane Szafron	Professor	60

Faculty involved in co-supervising the students listed below include Vadim Bulitko, Michael Buro, Rob Holte, Martin Müller, and Duane Szafron.

Postdoctoral Fellows, Programmer/Analysts and Support Staff

NAME	POSITION	PERCENTAGE
Neil Burch	Programmer/Analyst	100
Aaron Davidson	Programmer/Analyst	5
Markus Enzenberger	Programmer/Analyst	100
Amanda Hansen	Administrative Support	40
Matthew McNaughton	Programmer/Analyst	100
Carmello Piccione	Programmer/Analyst	100
Thomas Roy	Programmer/Analyst	100
Finnegan Southey	Postdoctoral Fellow	50
Nathan Sturtevant	Postdoctoral Fellow	100

PhD Students

NAME	TOPIC	AWARDS
Darse Billings	Imperfect information in poker	NSERC (past)
Adi Botea	Planning	University of Alberta
Maria Cutumisu	Behaviour patterns	NSERC
Markian Hlynka	Learning search control	NSERC (past)
Alex Kovarksy	Pathfinding	NSERC
Xiaochen Niu	Computer Go	NSERC
David O'Connell	AI applied to civil engineering	NSERC (past)
Jack van Rijswijck	Computer hex	University of Alberta
David Silver	Machine learning	Alberta Ingenuity
Ling Zhao	Satisfiability and planning	Alberta Ingenuity

MSc Students

NAME	TOPIC	AWARDS
Siddhartha Chinthapelly	Learning evaluation functions	
Douglas Demyen	Squad control in RTS games	
Bret Hoehn	Game theory	NSERC (past)
Morgan Kan	Computer poker	NSERC
Maryia Kazakevitch	Real-time search	
Leo MacDonald	Real-time search	
Jonathan Newton	Learning in games	

NAME	TOPIC	AWARDS
Curtis Onuczko	Pattern-based scripting	
Josh Ryder	Computer security	
Frano Sailer	Planning in RTS games	NSERC
Terence Schauenberg	Opponent modelling in poker	NSERC (past)
Jeff Siegel	Behaviour patterns	
Michael Smith	Computer billiards	NSERC
Gang Xiao	Learning for testability	
Jonathan Yip	Scripting in RTS games	NSERC (past)
Haizhi Zhang	Search algorithms	

COLLABORATIONS

Our group is actively working with several partners:

INDUSTRIAL
Electronic Arts (commercial games research)
Electronic Arts has funded us in the past with cash and graduate student internships. In the past year, they donated a copy of their most valuable asset to us: the source code to their FIFA 2004 product (valued at $1.4M).
BioWare (commercial games research)
BioWare sponsors our research with a cash contribution each year. They have committed to continue this financial arrangement for another three years, and have given us access to the source code for Neverwinter Nights (valued at $2M).
Relic (commercial games research)
We are finalizing negotiations for an in-kind donation to our group.
BioTools
This University of Alberta spin-off company has commercialized the poker research group's work.
PROVINCIAL
Joerg Denzinger, University of Calgary
Denzinger is working with us as part of our Intelligent Robotics and Intelligent Systems (IRIS) NCE funding.
Alberta Ingenuity Centre for Machine Learning (AICML)
This research centre was formed three years ago with Jonathan Schaeffer as one of the co-principal investigators. AICML is starting to work with a number of industrial partners.
NATIONAL/INTERNATIONAL
IKAT at the University of Maastricht (The Netherlands) and the Computer Games Laboratory at Shizouka University (Japan)
We have strong research ties with IKAT at the University of Maastricht (The Netherlands) and the Computer Games Laboratory at Shizouka University (Japan). This includes annual visits and graduate student exchanges.
WestGrid
This is a multi-institutional initiative (University of Alberta, University of British Columbia, University of Calgary, University of Lethbridge, Simon Fraser University, TRIUMF, and The Banff Centre) and multi-disciplinary initiative. Our industrial partners include Hewlett Packard, IBM, and Silicon Graphics.

INTELLECTUAL PROPERTY

Schaeffer is the co-founder of BioTools Inc. (http://www.biotools.com). Originally a bioinformatics company, in the past year it has been re-invented as a profitable games company. BioTools has commercialized the poker program (http://www.poker-academy.com), and is investigating working with us on other technologies.

Chenomx is a spin-off from BioTools (http://www.chenomx.com). Chenomx has developed revolutionary software technology to do fluid analysis. From a spectrogram produced by a NMR machine, our programs can analyze the data to a level of detail not easily possible in a laboratory. Our first application is to analyze urine. Conventional urine analysis (as prescribed by a doctor) returns the analysis of six (of over 250) compounds in the urine. Our software accurately returns an analysis of over 100 compounds, faster and at less cost. We have partnered with Varian and Breuker, the two largest NMR manufacturers in the world. Our product, Eclipse, is currently under evaluation by major pharmaceutical companies.

AWARDS

The following awards have been won by members of our group in the past year:

- Adi Botea, Markus Enzenberger, Martin Müller and Jonathan Schaeffer: Program MACRO-FF won three of the seven competitions it was entered in the biennial International Planning Competition.
- Akihiro Kishimoto (with Yashushi Tanase): Second place at the World Computer Shogi Championship (Japan).
- Yngvi Björnsson, Ryan Hayward, Mike Johanson, Morgan Kan, and Nathan Po: Silver medal at the Ninth Computer Olympiad (Israel) for the game of Hex.
- Markus Enzenberger: Fourth place finish at the Ninth Computer Olympiad (Israel) for the game of 9x9 Go.

FUNDING

Jonathan Schaeffer has received a significant grant from CFI ($4M), and a combined amount of (~$562K) from NSERC and NCE. Money from industry (~$7.5M) consists mostly of in-kind contributions. Provincial agencies such as ASRA ($2M) and AIF ($1.4M) have also contributed. Dr Schaeffer holds a Tier 1 Canada Research Chair which provides $200K per year.

PUBLICATIONS

JOURNALS

Y. Björnsson, R. Hayward, M. Johanson, J. van Rijswijck. "Solving 7x7 Hex with Domination, Fill-in, and Virtual Connections", *Theoretical Computing Science,* to appear, 2005.

M. Hlynka, J. Schaeffer. "Pre-Searching", *Journal of the International Computer Games Association*, December, 2004.

CONFERENCES

Y. Björnsson, M. Enzenberger, R. Holte, J. Schaeffer. "Fringe Search: Beating A* at Pathfinding on Game Maps", *IEEE Symposium on Computational Intelligence and Games*, to appear, 2005.

A. Botea, M. Müller, J. Schaeffer. "Learning Partial-Order Macros from Solutions", *International Conference on Planning and Scheduling* (ICAPS), to appear, 2005.

M. Buro, T. Furtak. "RTS Games and Real-Time AI Research", *Behavior Representation in Modelling and Simulation* (BRIMS), pages 27-34, 2004.

M. Buro. "Call for AI Research in RTS Games", *Challenges in Game Artificial Intelligence*, Report # WS-04-04, AAAI Press, pages 139-142, 2004.

J. Buchanan, F. Southey, R. Holte, G. Xiao, M. Trommelen. "Semi-Automated Gameplay Analysis by Machine Learning", *Game Developer Conference*, 2005.

M. Carbonaro, J. Schaeffer, D. Szafron, M. Cutumisu, M. McNaughton, C. Onuczko, T. Roy, S. Gillis, S. Kratchmer. "Interactive Story Writing in the Classroom Using Computer Games", *Digital Games Research Association Annual Conference* (DiGRA), to appear, 2005.

M. Chung, M. Buro, J. Schaeffer. "Monte Carlo Planning in RTS Games", *IEEE Symposium on Computational Intelligence and Games*, to appear, 2005.

A. Felner, U. Zahavi, J. Schaeffer, R. Holte. "Dual Lookups in Pattern Databases", *International Joint Conference on Artificial Intelligence*, to appear, 2005.

Z. Guo, D. Szafron, J. Schaeffer. "Using Generative Design Patterns to Develop Network Server Application", *10th International Workshop on High-Level Parallel Programming Models and Supportive Environments* (HIPS), to appear, 2005.

A. Kishimoto, M. Muller. "Dynamic Decomposition Search: A Divide and Conquer Approach and its Application to the One-Eye Problem in Go", *IEEE Symposium on Computational Intelligence and Games*, to appear, 2005.

A. Kishimoto. "A Correct Algorithm to Prove No-Mate in Shogi", in Japanese, *9th Game Programming Workshop,* pages 1-8, 2004.

M. McNaughton, M. Cutimisu, D. Szafron, J. Schaeffer, J. Redford, D. Parker. "ScriptEase: Generative Design Patterns for Computer Role-Playing Games", *International Conference on Automated Software Engineering* (ASE), 2004.

M. McNaughton, J. Schaeffer, D. Szafron, D. Parker, J. Redford. "Code Generation for AI Scripting in Computer Role-Playing Games", *Challenges in Game Artificial Intelligence*, Report # WS-04-04, AAAI Press, pages 129-133, 2004.

M. Müller, Z. Li. "Locally Informed Global Search for Sums of Combinatorial Games", *Computers and Games*, 2004.

X. Niu, M. Müller. "An Improved Safety Solver for Computer Go", *Computers and Games*, to appear, 2004.

J. Schaeffer, Y. Björnsson, N. Burch, A. Kishimoto, M. Müller, R. Lake, P. Lu, S. Sutphen. "Solving Checkers", *International Joint Conference on Artificial Intelligence,* to appear, 2005.

D. Silver. "Cooperative Pathfinding", *Artificial Intelligence and Interactive Digital Entertainment*, to appear, 2005.

F. Southey, R. Holte. "Semi-Automated Gameplay Analysis", *Challenges in Game Artificial Intelligence*, Report # WS-04-04, AAAI Press, 2004.

F. Southey, G. Xiao, R. Holte, M. Trommelen, J. Buchanan. "Semi-Automated Gameplay Analysis by Machine Learning", *Artificial Intelligence and Interactive Digital Entertainment*, to appear, 2005.

N. Sturtevant. "Leaf-Value Tables For Pruning Non-Zero Sum Games", *International Joint Conference on Artificial Intelligence*, to appear, 2005.

OTHER

A. Botea, M. Enzenberger, M. Müller, J. Schaeffer J, "Macro-FF", *International Conference on Planning and Scheduling booklet*, pages 15-17, 2004.

M. Cutumisu, M. McNaughton, J. Schaeffer, D. Szafron. "AI Scripting in Computer Role-Playing Games", *17th IEEE International Conference on Automated Software Engineering* (ASE)", refereed demo, 2004.

M. Müller. "Go-related Research at the University of Alberta", *Game Programmers Workshop* (GPW), pages 22-23, 2004 (extended abstract).

J. Schaeffer, M. Carbonaro, M. Cutumisu, S. Gillis, M. McNaughton, C. Onuczko, T. Roy, D. Szafron. "Interactive Story Writing Using ScriptEase", *Artificial Intelligence and Digital Entertainment* (AIIDE), to appear, 2005 (extended abstract for invited talk).

INVITED PRESENTATIONS

Vadim Bulitko. University of California (Berkeley), February 2005.

Vadim Bulitko. University of California (Los Angeles), February 2005.

Vadim Bulitko. Institute for Creative Technologies (ICT), February 2005.

Vadim Bulitko. Information Science Institute (ISI), February 2005.

Vadim Bulitko. University of Southern California (USC), February 2005.

Ryan Hayward. Oxford University, November 2004.

Ryan Hayward. University of Toronto, November 2004.

Rob Holte. Electronic Arts, May 2004.

Rob Holte. University of Ottawa, October 2004.

Rob Holte. University of British Columbia, December 2004.

Rob Holte. National Research Council (Winnipeg), December 2004.

Rob Holte. Goldsmiths University (London, UK), February 2005.

Rob Holte. University of Texas (Austin), March 2005.

Akihiro Kishimoto. 9th Game Programming Workshop in Japan, November 2004.

Martin Müller. 9th Game Programming Workshop in Japan, November 2004.

Jonathan Schaeffer. 17th International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems (IEA/AIE), June 2004 (Keynote Speaker).

Jonathan Schaeffer. University of Toronto, November 2004 (Distinguished Lecture Series).

Jonathan Schaeffer. Dalhousie University, February 2005.

Jonathan Schaeffer. Queen's University, February 2005 (Distinguished Lecture Series).

Jonathan Schaeffer. University of British Columbia, February 2005.

Jonathan Schaeffer. Electronic Arts, February 2005.

SOFTWARE ENGINEERING DECISION SUPPORT

Decisions are hard to understand and far from being optimal in terms of their quality. What can be expected from decision support in the area of software engineering is higher decision quality, improved communication between all involved parties, increased productivity, time savings, and improved customer satisfaction.

GUENTHER RUHE

iCORE Professor
Computer Science, Electrical and Computer Engineering and
Industrial Research Chair Software Engineering, University of Calgary
http://sern.ucalgary.ca/~ruhe

Qualified decisions related to software and system technologies, resources, processes and products are the drivers of an efficient economy. The main achievements of the laboratory of Software Engineering Decision Support (SEDS) over the last year have been breakthrough results in the area of intelligent support for strategic and early stage decisions in software and system development. We are following a multi-disciplinary research approach and have integrated concepts and approaches from software engineering, decision science, artificial intelligence, knowledge management, and computational intelligence to achieve innovative results. Research in the reporting year has resulted in four journal publications with 3 more in preparation, 18 publications at conferences or workshops, 6 book chapters, preparation of a special issue of the IJSEKE, and further progress on the book titled "Software Engineering Decision Support – Methodology, Tools and Applications" (to be published at CRC Press in 2007).

EXECUTIVE SUMMARY

Progress has been achieved in creating a core team of researchers and in establishing and enhancing national and international collaboration. The team attracted another iCORE International Award student. The former Post Doctoral Fellow and visitor Dr Pfahl successfully applied for a position at the University of Calgary, Department of Electrical and Computer Engineering. He joined the team in July 1, 2005.

Four NSERC related project initiatives have been launched. One NSERC CRD grant, Simulation-based Decision Support for Software Quality Assurance started in Fall 2004. Another grant, Intelligent Support for Release and Design Decisions for Evolvable Software-Intensive Systems, was conditionally approved pending finalization of IP agreement. An NSERC Strategic Research Grant proposal "Towards the Next Generation of IT Resource Management Systems – A Hybrid Intelligence Approach" was prepared with the City of Calgary as a non-academic partner. Additional financial support was launched in the NSERC "Idea to Innovation (I2I)" program for the proof-of concept project titled "Web-based Decision Support for Release Planning and Prioritization".

Further progress was made in pre-commercialization of the ReleasePlanner® decision support system. Successful trial projects were performed with Siemens Corporate Technology (Muenich), Trema Laboratories (Calgary), Nortel Networks (Calgary), Autodesk (Calgary), SoldiTech (Helsinki), and Ericsson Canada (Montreal). The technology was successfully presented at CeBIT'2005, the world's largest computer trade show.

The 16th International Conference on Software Engineering and Knowledge Engineering (SEKE'2004) was held in Banff in June 2004. It brought together leading researchers and industrial representatives. The program committee was chaired together with Dr Frank Maurer. The conference attracted the largest number of submissions in history. Thanks to additional iCORE support, outstanding keynote speakers could be invited; Shari Lawrence-Pfleeger, Dieter Rombach, and Lotfi Zadeh. Two follow-up workshop events have been approved for 2005/2006.

RESEARCH PROGRAM OVERVIEW

Objectives

The current maturity of software and systems engineering decision-making is low. Decisions are made ad hoc, not relying on validated models and sound methodology. Decisions are hard to understand and far from being optimal in terms of their quality. What can be expected from decision support in the area of software engineering is higher decision

quality, improved communication between all involved parties, increased productivity, time savings, and improved customer satisfaction. Our related research can be structured into three main areas.

- Advancing Software Engineering Decision Support (SEDS) methodology by multidisciplinary research
- Developing intelligence-based support methods and techniques for specific software engineering decision problems
- Tool development and empirical evaluation of its impact

Main Achievements

Technically, we have achieved the following main results:

Advancing SEDS Methodology

The paradigm of hybrid intelligence was further developed and refined. The advantage of the human intelligence based approach is that it is able to better handle soft and implicit objectives and constraints. The advantage of computer-based approach is exactly where the human based approach fails: to cover a large portion of the solutions space. Our hybrid approach is designed to combine the strength of both human and computational intelligence. The methodology of SEDS was further enhanced by creating synergy between decision-making and the contributions of simulation, e-assistants, explanation and different optimization techniques (genetic algorithms, integer programming, branch and bound, heuristics).

Uncertainty is an important issue in decision support. This is particularly true in software engineering where uncertainty is one of its key characteristic. We are particularly interested in decision problems that are not completely understood, have a large solution space and/or uncertain data, such as planning problems. We have developed the diversification principle to facilitate the participation of human expertise into the decision process without explicitly integrating it into formal models.

Intelligence-Based Decision Support for Specific Problems

We have further qualified and enhanced intelligent support in the area of release planning. This was done by providing explanations about 'why' certain alternatives were proposed. This issue is the most critical limitation of current decision support. We have designed a dialog approach that is applicable not only to release planning, but also to the more general class of "wicked" planning problems. In addition to that, we have enhanced the scope of release planning by allowing a flexible number of releases, by considering system characteristics for evolving systems, and by taking more flexible prioritization criteria into consideration.

After having designed and applied the paradigm of hybrid intelligence to the wicked problem of release planning (with successful development and application of a decision support system based on this idea), we have transferred these principles to three more classes of decision problems:

- Selection of Commercial Off The Shelf (COTS) software components
- Decisions about quality and how it affects time-to-market
- Value-based prioritization and planning

Decision Support System Development and Empirical Evaluation

Further progress was made in the development and evaluation of the ReleasePlanner® decision support system; a tool suite that provides flexible, web-based tool support for assigning requirements or features to releases such that the most important risk, resource, and budget constraints are fulfilled. It can be used in different user modes and provides intelligent decision support for any kind of iterative development. US and Canada patent protection is pending.

Successful trial ReleasePlanner® projects were undertaken with Siemens Corporate Technology (Muenich), SoldiTech (Helsinki), Trema Laboratories (Calgary), Nortel Networks (Calgary), Autodesk (Calgary), and Ericsson Canada (Montreal). The technology was presented at CeBIT'2005, the world's largest computer trade show. A series of promising new contacts were obtained from this event, including Verizon Information Services (US), Applied Biosystems (US), Hyperwave (Austria), Schlund+Partner (Germany), ELCON (Germany), Tranzeo (Vancouver), SmartTechnologies (Calgary), and Wi-Lan (Calgary).

RESEARCH PROJECTS

Diversification of Solution Alternatives

In this research, as mentioned above, we propose the diversification principle to facilitate the participation of human expertise into the decision process without explicitly integrating it into formal models. Instead of just one optimal solution, the diversification principle suggests the consideration of a small set of qualified solution alternatives that are as diversified as possible. This diversification can help the decision maker obtain more insight and detect new aspects of the problem. The diversification principle is materialized by a meta-model consisting of a core optimization model, a metric in the solution space, and a strategy

to obtain diversification. Though the diversification principle arose in our research in software engineering, it can also be applied in any decision problem having a large solution space where optimization is indispensable but never sufficient.

Comprehensive Software Release Planning (CSRP)
Very often, release planning is handled informally and in an ad hoc manner. Recently, we introduced the EVOLVE* method, which incorporates an evolutionary framework of performing successive steps of modeling, generation and exploration of solution alternatives and evaluation and consolidation. In our research, we have extended the applicability of the approach to software release planning of systems with maintenance considerations. By exploiting a specialized problem formulation allowing the application of mixed integer programming, we achieve better results from a more flexible allocation of involved resources. The comprehensive approach called CSRP allows planning for a flexible number of releases under different types of resource and technological constraints.

Supporting Software Release Planning Decisions for Evolving Systems
Large-scale software systems constantly change during system evolution involving feature enhancement. Most of the features originate from diverse stakeholders that require their needs to be met despite resource and risk constraints. In such large systems, the number of features requested during the different releases of the system typically exceeds the available resources. Release planning involves decision making about which new features or changes should be implemented during which release of the software. Existing release planning techniques are not targeted at evolving systems; in this case, knowledge about the existing software product is core to making meaningful release decisions.

We have described ten key technical and non-technical aspects impacting release planning. Based on these aspects, we evaluated seven existing release planning techniques. We have also proposed a new release planning framework that considers the effect of existing system characteristics on release planning decisions. Initial realization of this framework focuses on historical defect data to characterize the health of system components. This proposed approach extends the existing solution method called EVOLVE* by the proactive analysis of the risk involved in integrating new features into existing components of the system and identifying the importance of estimating the integration effort for each feature based on system characteristics.

Decision Support for the Customization of the COTS Selection Process
Software technologies need to be customized to make them effective and efficient for a specific context. We have considered customization of the COTS selection process. We have developed a methodology which customizes the selection process based on the actual project domain characteristics, including attributes such as available effort or project criticality. The customization of the process is done at both the process level and the activity level. We suggest a hybrid approach that integrates formalized knowledge

Guenther Ruhe and some research team members at the 2005 Banff Informatics Summit

(From left to right)
Thamer Al Boura'e, Sebastian Maurice, Pankaj Bhawnani, Jim McElroy, Ahmed Al-Emran, Abdallah Mohamed, Omolade Saliu, Guenther Ruhe, Kornelia Streb, Gensheng Du, Eric Bauld, Jingzhou Liv

with human expertise. This principle has already been successfully used in the context of software release planning. The advantage is two-fold: First, we exploit the existing empirical results related to different stages of the COTS selection process. Second, we facilitate involvement of human judgment to determine the most appropriate decisions among the ones proposed by the formalized and knowledge-based solution techniques.

Uncertainty Handling in Tabular-based Requirements Using Rough Sets

Software requirements management is an essential process to better understand, identify, derive, control and improve system requirements. Typically, requirements are unclear at the beginning and evolve over time. Uncertainties usually result in conflicts among requirements. Rough set analysis (RSA) is a promising technique of granular computing. The emphasis of this research is on formally defining three software requirements uncertainty problems and applying RSA to solve these problems. A systematic approach called MATARS was developed for this purpose. We use a modification of a real world software requirements specification (SRS) benchmark example to illustrate the main concepts and ideas of the approach.

Reliability Driven Decision Support for Incremental Software Development

In the 2002 Standish Group report it was observed that 84 percent of software projects are incomplete and erroneous when released, so deciding on whether a software version should be released remains a big challenge. This becomes even more difficult in the case of incremental software development where the requirements keep changing frequently. A reliability driven decision support approach was proposed to study the effects of defect repository patterns on software release decisions. We have evaluated the suitability of existing reliability models in guiding release decisions. The case study presented reveals the impact of project and domain specific uncertainty factors such as risk, testing effort and target reliability on time to market decisions for the software release when the underlying assumptions made by existing reliability models are violated.

Guenther Ruhe

Effort Estimation for Release Planning

A hybrid method is proposed for effort estimation at the requirement/feature level as well as the project level by combining experience reuse, expert judgment and analogy-based approaches. After discussing the organization of the experience base, qualitative similarity measures for attributes were defined based on a categorization of attribute values. Analogy-based effort estimates are provided based on local similarity measurements between attributes and global similarity measurements between objects. The final effort estimates are aggregated from the analogy-based estimates and expert judgment. Experience maintenance and organizational learning activities are also proposed to keep the experience up to date. Two data sets are used for the validation of our method; one is from a student project, another one from the International Software Benchmarking Standard Group (ISBSG).

Decision Support for Software Release Planning Using e-Assistants

In this research, uncertainty and incompleteness of available information is addressed by a more flexible planning procedure including e-assistants. We are proposing a hybrid approach called e-release planning combining the strengths of computational intelligence with human intelligence. The e-assistants provide support to generate the most promising sequence of problem instances to be solved. They interact with the human stakeholder and the project manager to elicit their implicit preferences based on their individual evaluation of the proposed solutions. During the iterative approach, we incrementally fix requirements to their most favorable assignment to a release. This decision is based on analyzing concordance and non-discordance of assignments of requirements to releases between the candidate solutions. The intelligent decision support tool ReleasePlanner® is used as the underlying 'solution generation engine'.

Evaluation of Operational Feasibility of Strategic Release Plans

Strategic planning needs to be supplemented by the more fine-grained operational release planning typically performed in project management. Operational

planning, as a refinement of strategic planning, is performed for the next immediate release. In this research, we present the improvements in software development processes and products by performing the evaluation of the operational feasibility of strategic software planning. We also present the use of the research prototype ReleasePlanner® in a real-world situation through a case study at Trema Laboratories Inc. and report on the improvements achieved.

Decision Support for Value-Based Software Release Planning

Incremental software development replaces monolithic-type development by offering a series of releases with additive functionality. In this research, we have extended the existing hybrid intelligence based release planning method called EVOLVE* to accommodate financial value in the form of net present value estimates of proposed features. This extension enables us to perform financial value-based software release planning. The results show that the F-EVOLVE* model may be used to decide which features to produce when based on their financial contributions. Specifically, F-EVOLVE* may be used to determine which features generate the highest returns, with shortest development times.

Staffing for Software Inspections – An Empirical Study

Software inspection is an important means to verify and ensure high quality in software development projects. Many proposals have been suggested and used to improve Fagan's inspection method. Various publicly published data have already clearly demonstrated the effectiveness and efficiency of software inspection. However, few empirical studies are currently available to guide the appropriate selection of inspectors based on their experience and skills. This research has been devoted to an exploratory empirical study to address this open question. The empirical study reveals the cause-effect relationship between certain observable experience levels and skills of inspectors, and the number of defects actually found in the requirement document.

The results indicated that software design and testing experience had the strongest influence on the reading effectiveness of software requirement documents. On the other hand, coding experience has the least effect. These results provided further insight for the design of a subsequent study. Rough-set based data analysis provided production rules to help decision makers on future projects better choose their inspectors.

A Dialogue Approach for Solving Wicked Planning Problems

In this research we have considered an interactive and explanation supported approach to planning problems that are not only wicked but also complex. In our approach we concentrate on the communications between agents. These are organized in the form of a dialogue between agents of an explanatory character. This explanation method differs essentially from the methods used in traditional expert systems. During the dialogues stakeholder opinions can be changed or withdrawn, even if they are formulated as hard constraints (that is, the constraints that cannot change). This method is generic enough to be applied to any wicked and complex planning problems. Therefore, we also present one of the applications of this method in release planning.

An Explanation Component for Software Release Planning

Acceptance of decision support solutions offered by software systems is largely determined by the degree of trust and understanding of the results by the end-users. The generation of explanations can be regarded as running a sequence of coordinated problem instances and making sense out of the related results. This research has provided a taxonomy for identification of question-types and answer-types for an explanation component called EXPLAIN-RP that provides decision support for software release planning. Release planning is a very complex optimization process by which a set of requirements are assigned to different releases of software development to maximize technological, effort, time and budget utilities. Explaining results arising from such complex process is very necessary for end-user understanding and trust. The question-types and answer-types identified within this context are meaningful and interesting to EXPLAIN-RP users.

OBJECTIVES FOR NEXT YEAR

Intelligent Support for Release and Design Decisions of Evolvable Software-Intensive Systems

Hybrid Intelligent Systems (HIS) are a promising area of research due to the applicability of HIS to many complex and real world problems. HIS combine and integrate the strengths of multiple automated and semi-automated approaches to collect and analyze both qualitative and quantitative data. Such integration is necessary as neither human nor computational

intelligence alone are able to provide sufficient release planning and software design decision support to achieve cost-effective evolvable systems. Humans are better able to handle soft and implicit objectives and constraints; computational intelligence is better able to handle a wide search through a large solution space. We will create and apply HIS in two innovative directions:

- As the foundation of a methodology to support decision-making for release and design decisions
- As a new paradigm to generate, activate, and exploit knowledge for generating, evaluating, and explaining alternatives for release and design decisions.

We are working on a hybrid methodology for generating qualified solution alternatives for release and design problems under risk and resource constraints. The methodology will be based on the hybrid and customized use of modelling and simulation, genetic algorithms, and integer programming. It will overcome the limitations of current solution approaches in terms of its scope and its proactive decision support capability. No comparative results for this research question are currently available.

Dynamic Release Planning and Software Project Monitoring

Current planning is static in the sense that is does not consider any aspect of execution of the plans other than estimates of the resources required. However, software development and evolution is a dynamic process with a large number of impacting factors. To better accommodate this dynamic character including feedback loops within the process, we will investigate software process simulation for modeling and executing the individual tasks related to the features to be assigned to releases. This will result in a better validity of the proposed plans. If done for the different types of resources involved, this will further allow project monitoring by comparing the planned tasks and their comparison with actual performance.

Open Scope Release Planning

Releases may also be arranged according to open scope release planning, where release times are not predefined. If this approach is used, the definitions of the release times and the requirements or features assigned to the respective releases are obtained as results. In this case, a solution may be sought that minimizes the time between releases, since the earlier a release is issued, the earlier it generates value such as money. Another point to consider is whether there is any sub, or otherwise related, products. In this case, each may have its own release planning goals, however, for the overall products the different cycles have to be synchronized. This can be modeled and solved using integer programming. The notion of "open scope planning" can be extended to address synchronization of releases as requested in any kind of embedded product development where you have to address planning of different parts (hardware, software, middleware). Each of these components is an open scope problem. However, for the final product, planning for all the components has to be synchronized because of the mutual dependency between the components. The solution is approached through a formal description of the problem that uses binary variables and applying genetic and integer programming optimization algorithms.

Fast Heuristics and Integer Programming Solution Algorithms

Current solution algorithms for release planning are based on genetic algorithms. These algorithms cannot guarantee optimality. We are working on fast (knapsack-type) heuristics able to generate good solutions for large-scale and complex problems in very short time. We will further analyze and fine-tune parameters for genetic algorithms and comparative analysis between heuristic, exact (integer programming) and evolutionary optimization algorithms. The results will be used to extend the functionality of ReleasePlanner® by providing features for handling uncertainty of data, fuzzy effort, and risk and dependency constraints. This includes the development of on-line user support to optimally customize the algorithms in dependence of the problem parameters.

Explanation Component for Release Planning Decision Support

Explanation is intended to increase acceptance of the tool, to improve understanding of the results, and to increase applicability and acceptance of suggested solutions. The ReleasePlanner® explanation scenario involves three types of agents (participants): the system that provides the solution to the problem. In our context a software agent; the user who obtains the solution for further treatment, in our context a human agent; and the explainer who explains the system's solution to the user, in our context a software agent.

We are mainly interested in the explainer agent. The explanation agent needs knowledge about the other agents. More precisely, the explainer needs an understanding of how the system obtains the solution, and a model of the user. A user model in general describes

- What the user knows and
- What the user wants or needs to know. In some way, one can think of an explanation as an answer to (yet) unexpressed questions of the customer;

therefore somehow the concept of a dialog enters the scenario. In particular, two types of explanations must be distinguished:

a) One-step explanations, provided only once, and

b) Dialog-type explanations that proceed in several steps. Both types contain a communication aspect, for a) it is degenerated.

Decision Support for Value-Based Software Technologies

A value-based approach to software engineering involves a different focus and approach to developing software. Meeting the needs of customers is as important as justifying the development efforts needed to meet those needs. In today's world with rapidly changing consumer demands, informational technology, and marketplaces, the requirements are changing rapidly requiring quicker adaptability by market participants. The critical success factor in this world for software developers is responding to changing requirements quickly while maintaining a focus on their value proposition which may be a quicker return on investments or an improvement in a public service like health, education, and defense.

Modeling and Implementation of Software Agents Decision Making

Software agents are knowledgeable, autonomous, situated and interactive software entities. Agents' interactions are of special importance when a group of agents interact with each other to solve a problem that is beyond the capability and knowledge of each individual. Efficiency, performance and overall quality of the multi-agent applications depend mainly on how the agents interact with each other effectively. In this chapter, we suggest an agent model by which we can clearly distinguish different agent's interaction scenarios. The model has five attributes: goal, control, interface, identity and knowledge base. Using the model, we analyze and describe possible scenarios, devise the appropriate reasoning and decision making techniques for each scenario, and build a library of reasoning and decision making modules that can be used readily in the design and implementation of multi-agent systems.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

Faculty Team Members

NAME	
Dr Maurer	Department of Computer Science
Dr Denzinger	Department of Computer Science
Dr Walker	Department of Computer Science
Dr Far	Department of Electrical and Computer Engineering
Dr Wang	Department of Electrical and Computer Engineering

Postdoctoral Fellows

NAME	ROLE/TOPIC
Dr An Ngo-The	Soft Computing in Software Engineering Decision Support
Dr Dietmar Pfahl	Fraunhofer Institute for Experimental Software Engineering: Simulation-based Decision Support
Dr Michael M. Richter	Professor emeritus, Department of Computer Science, University of Kaiserslautern: Reasoning and explanation in decision support systems

PhD Students

NAME	ROLE/TOPIC
Gensheng Du	Intelligent Explanation Component for Software Release Planning
Jingzhou Li	Effort Prediction for Release Planning Using Collaborative Filtering
Jim McElroy	Use-case Driven Planning of Software Releases
Abdallah Mohamed	COTS Software Product Selection
Michael Ochs	Fraunhofer IESE, Co-Supervisor: Efficient and Effective Management of COTS Assessment and Selection
Omolade Saliu	iCORE International Graduate Student Scholarship Award: Supporting Software Release Planning Decisions for Evolving Systems
Tom Watanaya	Co-Supervisor: Agent-based COTS Product Selection Method

MSc Students

NAME	ROLE/TOPIC
Pankaj Bhawnani	iCORE International Graduate Student Scholarship Award: Quality-based Software Release Decisions
Thamer Al Boura'e	Impact Analysis for Parametric Release Planning
Ahmed Raihan Al-Emran	Intelligent Tool Support for Decisions in Software Engineering
Zhizhong Li	Management of Tabular-based Requirements Using Rough Sets
Sebastian Maurice	Decision Support for Value-Based Software Engineering Release Planning
Yuhang Wang	Machine Learning for Improving Performance of Software Inspections

Undergraduate Students

NAME	ROLE/TOPIC
Erik Bauld	Database Management for ReleasePlanner®
Brad Cossette	Import and Export Functionality for ReleasePlanner®
David Goodlad	Back-end Algorithms for ReleasePlanner®
Gregory Spiers	User Interface for ReleasePlanner®
Kenny Tsang	Analysis Wizard for ReleasePlanner®

Support and technical staff

NAME	ROLE/TOPIC
Kornelia Streb	Assistant

INTERNATIONAL
FRAUNHODER IESE AND FRAUNHOFER-CENTER MARYLAND
In accordance to the Academic Cooperation Research Exchange between the University of Calgary and the Fraunhofer Institute for Experimental Software Engineering (Fh IESE), the Laboratory for Software Engineering Decision Support and Fh IESE agreed to a collaborative research and personnel exchange. On this basis, Dr Dietmar Pfahl has visited the laboratory for three months.
UNIVERSITY OF NEW SOUTH WALES
A similar agreement as signed with Fh IESE is in preparation to be signed with the research group of Dr Ross Jeffrey at University of New South Wales. Based on this agreement, the intention is to conduct joint research and exchange PhD students.
UNIVERSITY OF SANNIO, ITALY
A collaboration agreement between Research Center for Software Technologies and the Laboratory for Software Engineering Decision Support is in preparation. It covers joint research in the area of soft computing for decision support and the exchange of researchers.
INFORMAL COLLABORATIONS
Informal collaborations were launched, especially with the groups of Dr Lionel Briand (Carleton University, Canada), Dr Jens Jahnke (University of Victoria, Canada), Dr David Raffo (University of Portland, USA), and Dr Shari Pfleeger (RAND Corporation).
INDUSTRIAL COLLABORATION
SIEMENS CORPORATE TECHNOLOGY
Siemens Corporate Technology (SE3) is performing strategic planning of IT services to their business units. For that purpose, ReleasePlanner® is used. At a first stage, the road-mapping process is performed internally. At a second stage, external stakeholders will be integrated into the prioritization process. The prioritization will be done accordijng to urgency and risk considerations.
CITY OF CALGARY
An NSERC Strategic Research grant was prepared with the City of Calgary. It is devoted to a new generation of Information Technology (IT) resource management planning systems. The IT business unit at the City of Calgary is a multi-disciplinary organization that works with different divisions in building IT solutions, and then supporting these solutions for The City of Calgary. The IT department currently has over 100 projects in development. Another 200+ potential projects have been identified for development consideration. IT also supports over 600 systems currently in production, including their affiliated infrastructure requirements. The resource management function in this environment is very difficult. When building systems, resources from across the IT discipline are required at different times during the systems' development life cycles to bring a solution from inception to production and into support.
CHARTWELL TECHNOLOGIES
Chartwell Technology Inc. develops online games for the Web, PC and mobile phones. The approximately 30 games are delivered to approximately 20 clients world wide and include single player (for example: blackjack) and multiplayer games (for example: poker). Chartwell also produces a set of back-office tools for monitoring and reporting on game play and for collection of royalties. The medium-term goal is to provide decision support for Chartwell's release planning that incorporates risks associated with changing specific modules within the system. The long-term goal is to automate the determination of risk based on historical data collected in Chartwell's source code management system and to use these measures to augment the release planning and decision support systems.
SECURAC AND WESTJET
There are ongoing meeting to include WestJet as trial partner into the CSER project described in section 6.3. The idea is to use their measurement data and process models as input for the decision support system development. WestJet also articulated strong interest in using ReleasePlanner® for their strategic and operational planning of projects. The prioritization will be done according to the defined strategic business goals and to what extend these projects would match them.
TREMA LABORATORIES
Trema Group is a provider of strategic software solutions for the financial industry. The software development focus is on providing a fully integrated cash and treasury management product suite designed to support front to back office treasury operations, as well as specific applications for cash management and accounting. Requirements are added to the product incrementally. So, planning for future releases becomes extremely important for the business. At the end of the trial of using the intelligent decision support for both strategic and operational release planning at Trema Laboratories Inc., the general agreement is that ReleasePlannerTM provides benefits to the organization. Some of these benefits are tangible and some are intangible. The intangible benefits are difficult to realistically evaluate but the good thing in this study is that most of the intangible benefits are generally positive.
TRIAL APPLICATIONS OF RELEASEPLANNER®
Further progress was made in pre-commercialization of the ReleasePlanner® decision support system. Successful trial projects were performed with Siemens Corporate Technology (Muenich), Trema Laboratories (Calgary), Nortel Networks (Calgary), Autodesk (Calgary), SoldiTech (Helsinki), and Ericsson Canada (Montreal). The technology was presented at CeBIT'2005, the world's largest computer trade show. A number of promising new contacts and statements of interest were launched.

MULTIDISCIPLINE OR MULTI-INSTITUTIONAL PARTNERSHIPS
CSER
An NSERC CRD proposal titled "Simulation-Based Decision Support Software Quality Assurance" was conditionally approved. The project is part of the (Canadian) Consortium for Software Engineering Research. Created in 1996, CSER is a multi-party, industry-led research program, geared toward solving selected industrial problems in software engineering. The project called SimQuali aims to benefit the collaborators, their students and the Canadian economy in various ways. As a small company, Securac cannot afford to support a research department. This project provides opportunity for Securac to benefit from the collaborative research results embedded in an interaction/argumentation device when discussing trade-offs in software quality improvements and outcomes. The intelligent decision support tool will provide the capability to evaluate the outcomes of feasibility alternatives based on standard variables for verification and validation techniques.
INTERNATIONAL SOFTWARE ENGINEERING RESEARCH NETWORK (ISERN)
The Software Engineering research group at the University of Calgary successfully applied to become a member of the International Software Engineering Research Network ISERN. This gives us excellent opportunities to further extend collaboration with leading researchers and research institutions all over the world. For a list of the 33 member organizations, see http://www.iese.fhg.de/network/ISERN/pub/isern.list_of_members.html.
SECCO
The Software Engineering Consulting Consortium (SECCO) was formed with the objective of fostering and encouraging links between the industry and graduate students in the Software Engineering discipline engaged in research activities. SECCO is an organization operated by Software Engineering graduate students under the direction of the Software Engineering Decision Support (SEDS) lab (http://www.seng-decisionsupport.ucalgary.ca/). The objectives of SECCO are to be run not for profit, grow at a challenging and manageable rate, and to provide avenues for interaction between software engineering graduate students and industry. The mission of SECCO is to provide industry access to cutting edge technologies in the area of SEDS and promote applied research and empirical validation of new technologies as part of the graduate education.

INTELLECTUAL PROPERTY

ReleasePlanner®

While the release planner technology builds on a web-based approach, it has also been designed and developed to be easily customizable for the different types of users and different application scenarios. University Technology Inc. (UTI) has evaluated the technology for patent protection and determined that the objective function and consolidation process is both novel and patentable and has initiated the patent application process. UTI is actively involved in managing this process. Due to the fact that this technology can service a broad horizontal market, the potential for securing multiple follow-up patents is also a positive opportunity. US and Canada patent protection is pending. The research will also produce additional, valuable intellectual property such as the know-how generated through broad-ranging applications of the technology.

FUNDING

This year Guenther Ruhe received funding from NSERC (~$160K) which was added to his iCORE Professorship award ($350K/year). He also received $25K from industry and is pursuing other sources of industry funding for potential commercial spin-offs of his ReleasePlanner® software.

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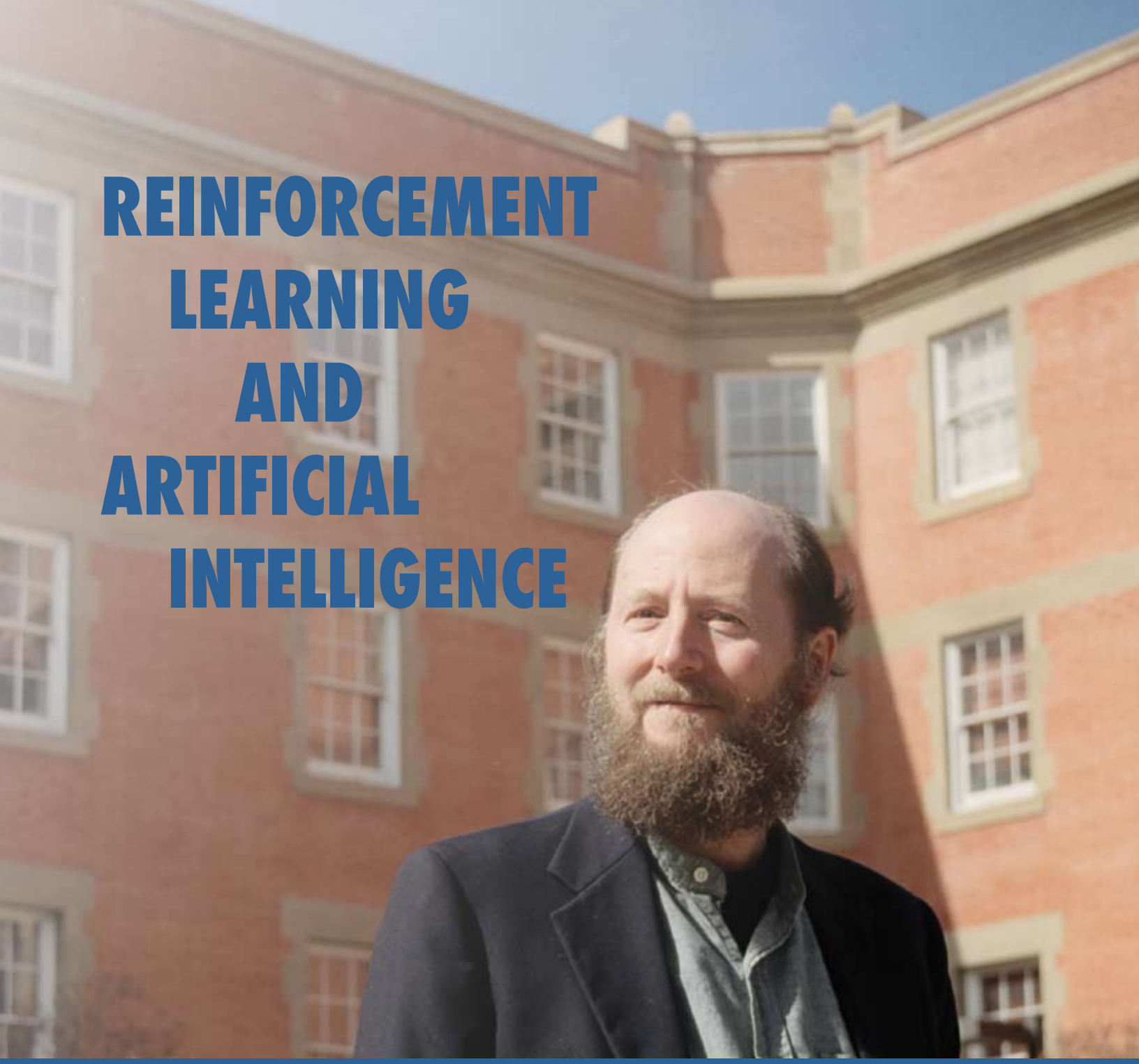

REINFORCEMENT LEARNING AND ARTIFICIAL INTELLIGENCE

The primary focus of the research program this year has been on how intelligent machines represent their knowledge of the world. The key issue here is expressing knowledge in such a way that it can be verified, learned, and used without continuous human input.

RICHARD SUTTON

iCORE Chair
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A vast number of problems of economic and scientific interest involve sequences of actions where the effects of one action influence the expected utility of subsequent actions. These sequential decision problems include such diverse applications as inventory management, the control of robots and industrial processes, playing backgammon, and planning under uncertainty, all of which are made more challenging because of their sequential and stochastic aspects. Reinforcement learning is a new body of theory and techniques for solving sequential decision problems, based on classical methods such as dynamic programming and inspired by animal learning theory, that enables larger and more diverse problems to be solved.

EXECUTIVE SUMMARY

The objectives of the Reinforcement Learning and Artificial Intelligence (RLAI) research program are to create new methods for reinforcement learning that remove some of the limitations on their widespread application and to develop reinforcement learning as a model of intelligence that could approach human abilities.

In this second year, the RLAI research team has grown to about 32 members, 21 of whom are graduate students and, of those, 11 are recipients of major scholarships. The output of the research program has also grown, with 21 papers published or accepted for publication in archival venues during the reporting period.

The primary focus of the research program this year has been on how intelligent machines represent their knowledge of the world. The key issue here is expressing knowledge in such a way that it can be verified, learned, and used without continuous human input. This project has pursued an unusual research strategy in which the knowledge is expressed in terms of the machines' sensors and actuators, which enables verification and learning. A new knowledge and learning technology has been developed that generalizes from low-level sensations and actions to higher-level concepts that could enable faster solution of much larger problems. Several proof-of-concept systems have been developed this year using small problems; larger problems will be used next year to extend and test the ideas. These results may be a conceptual advance toward a long-standing objective of informatics: a general technology of learning and reasoning about the optimal control of dynamical systems.

RESEARCH PROGRAM OVERVIEW

The iCORE research program in RLAI pursues an approach to artificial intelligence (AI) and other engineering problems where they are formulated as Markov Decision Processes (MDP) and approximately solved using Reinforcement Learning (RL). RL is a new body of theory and techniques for solving MDPs that has been developed in the last 20 years primarily within the machine learning and optimal-control research communities. RL researchers have developed novel methods to approximate solutions to MDPs that are too large or too ill-defined for classical solution methods such as dynamic programming. For example, RL methods have obtained the best known solutions in such diverse automation applications as helicopter flying, elevator scheduling, playing backgammon, and resource-constrained scheduling.

The iCORE research proposal identified four focus areas for investigation, substantial progress was made on each this year.

- One proposed focus was on predictive state representations; a new set of ideas for modeling sequential decision problems that are not

Markov, that is, for which an appropriate state representation is not available a priori but must be constructed from the stream of raw sensor data.

This year we have introduced temporal-difference networks; a new formulation that extends prior work on predictive state representations to include temporal-difference learning, the core component of most RL algorithms. Temporal-difference networks appear to be a qualitative advance over previous work in machine learning in that they explicitly represent the goals of the learning process. This enables a wide variety of complex goals, and enables the choice of goals to be made by the machine rather than by people.

- A second proposed focus was on temporal abstraction, the extension of RL beyond the flat and low-level representations commonly used with MDPs to the more flexible, structured, and higher-level representations used by AI systems. The ability to represent knowledge about possible courses of action at a multiplicity of interrelated temporal scales would vastly increase the generality and range of application of RL methods. The existing theory of options was proposed to be extended in this direction.

  This year we have integrated the options framework with temporal-difference networks. Simple temporal-difference networks make predictions at each time step that are conditional on the primitive action taken on that time step. Our extension enables the predictions to be conditional on options — multi-step closed-loop ways of behaving — rather than only on primitive actions. The options framework itself had to be substantially generalized in several ways to permit this extension. Work to date has been proof-of-concept demonstrations on small problems.

- A third proposed focus was broadly concerned with approximation and generalization in RL. Approximation is required in all large-scale applications yet is incompletely understood in both theory and practice. It was proposed to create an RL toolkit to facilitate the use of approximation and other RL techniques in applications.

  In this year we have completed and released the first version of the RL toolkit. RL Toolkit 1.0 is currently used in this research program and by reinforcement learning researchers throughout the world.

- The fourth proposed area of investigation was the demonstration of advances in the first three areas in robotics applications.

  This year we have established a dedicated robotics laboratory, acquired a variety of new robots, and completed our first robotic demonstrations of reinforcement learning.

These achievements are discussed in more detail in the following section.

Richard Sutton and
Minister Victor Doerksen

RESEARCH PROJECTS

Temporal Difference Networks

It has long been a goal for AI systems to be able to express their knowledge in terms of their interaction with the world. Connecting knowledge to experience provides a way of verifying and learning it autonomously. This ability may be essential to the practical development of large AI systems. This year we have taken further steps toward the goal of grounding knowledge in experience. We have introduced a new framework and learning algorithm called "temporal-difference networks". Temporal-difference networks translate world knowledge into explicit predictions of future experience that can be compared with actual experience. A major conceptual advance was to have the predictive questions asked about experience in machine readable form (and not just their answers); prior work with prediction learning has taken the questions to be implicit, in the human designer's mind but not in the machine's. Representing them explicitly enables the set of questions being asked to be large and subject to autonomous elaboration.

Grounding knowledge in experience is challenging because knowledge is high-level and conceptual whereas experience is low-level and sensori-motor. Several levels and types of abstraction are required to bridge the gulf. Temporal-difference networks combine two recently developed abstraction technologies: predictive state representations for abstracting over state, and the options framework for abstracting over time. Temporal-difference networks are still a very new idea and their strengths and limitations have yet to be fully determined. This year we have introduced the idea and shown some of its potential in micro-worlds; small problems where the knowledge and abstractions that need to be learned can be completely understood.

Four papers on temporal-difference networks have been submitted and accepted for publication. The paper introducing the idea was accepted for oral presentation at the prestigious Conference on Neural Information Processing Systems. Only three percent of the more than 800 papers submitted were selected for oral presentation at that meeting. Two other papers were accepted for publication at the International Joint Conference on Artificial Intelligence. One concerned extending temporal-difference networks to include history information, as in k-order Markov models. The other was a test of the utility of the primary idea underlying predictive state representations. The fourth paper extended temporal-difference networks to incorporate eligibility traces and to provide a conceptual bridge from them to Monte Carlo methods. A fifth paper describing the extension to include options is in preparation.

Function Approximation, Off-policy Learning, and Recognizers

Off-policy learning is learning about one way of behaving (the target policy) while actually behaving in some other way (the behavior policy). The problem of off-policy learning is that classical bootstrapping RL methods such as Q-learning, TD(λ), and dynamic programming can become unstable during off-policy learning, if function approximation is used. As both bootstrapping and function approximation are thought to be essential for large-scale applications, and off-policy learning is currently seen as necessary for learning temporally abstract system models, this instability is a key stumbling block to extending RL abilities.

This year we have empirically tested and mathematically analyzed a variety of off-policy learning algorithms, including least-squares methods and importance-sampling methods. A severe problem with these methods is that they have very high variance, causing learning to be very slow. As part of the work with temporal-difference networks, we have developed a new concept, that of a "recognizer," which appears promising in this regard. A recognizer observes behavior and accepts it, or not, as something that it is learning about. It recognizes a portion of the behavior as, in effect, corresponding to the target policy. Recognizers are used to condition the predictions made by temporal-difference networks on the options taken. Recent experiments suggest that importance sampling using recognizers has lower variance and is much better behaved than previous importance-sampling methods for off-policy learning.

Rich Sutton with some research team members

RL Toolkit

The RL Toolkit is a collection of software and guidelines to facilitate the development of RL research and applications. The first version of the toolkit was completed this year. RL Toolkit 1.0 includes:

- A standard interface for connecting reinforcement learning algorithms to reinforcement learning problems
- A variety of examples of using the interface
- An efficient implementation of tile coding, a popular function approximation method for domains with continuous state variables
- An implementation of eligibility traces for tile coding
- A graphics language "G" that is portable across Apple, Unix, Linux, and Windows machines
- Utilities for easily generating two and three dimensional graphs using G
- Five programs demonstrating reinforcement learning and the use of the toolkit. Early in the year we switched our primary development language from Lisp to Python, a popular open-source programming language that is available for almost any kind computer and that is easy to learn and use. Almost all of RL Toolkit 1.0 is written in Python. Some of the lower-level tools are written in the language C++ to maximize efficiency.

The RL Toolkit is used within the RLAI group and by other researchers and students throughout the world. It has been used in two courses at the University of Alberta, leading to several of the examples that are now part of the toolkit proper. The RL Toolkit software has been placed in the public domain.

Open Pages and the RLAI Web Site

An extensive new web site has been developed to coordinate and encourage RLAI research across the world. The web address for the site is http://rlai.net. The web site contains information about this project, pointers to other RL research groups, substantial discussion of a variety of research topics, and information about the RL Toolkit and related RL software tools.

The RLAI website was created using a new set of tools for collaborative authoring of web pages which were developed as part of this research project. The open pages system has three key features. First, it encourages a community of researchers to create and author web pages jointly. Literally anyone can edit or add to any open page. The open pages software prevents two authors from accidentally writing over each other's work and provides an archiving mechanism such that previous versions of an open page can be restored if necessary. The second key feature of open pages is that they are edited "in place." An author or editor does not download and work with web pages locally and then transfer them to the website. Instead the web pages are presented as directly editable and saved out to the web site just as one might save a file locally. These first two features are available with existing software tools such as "wikis," but the open page system appears to be unique in its third feature, which is that its pages can be edited in the WYSIWYG (What You See Is What You Get) style that we are all familiar with from modern word processors. That is, as you edit a page it appears just as it will when published on the web. This is in contrast to wikis, which are edited only in a low-level text mode in which textual codes are used for formatting of headings, fonts, bolding and so forth. These three features work well together in encouraging authoring and frequent maintenance of web pages, which in turn encourages their timeliness and accuracy.

Robotics Research

The RLAI robotics effort has acquired 20.6m^2 of dedicated laboratory space on the ground floor of the Computing Science Center. Several new robots have been acquired over the past year, including 8 Aibo robots, a Pioneer mobile robot with laser range-finder, and a Segway robot. The recently commercialized Segway Robot Mobility Platform (RMP) is a robust, fast, industrial-strength, indoor-outdoor robot platform. Based on the Segway Human Transporter (HT), it provides an excellent opportunity for exploring human-robot coordination. In the past six months an RMP and HT have been acquired and the basic work has been done to prepare the RMP as a research platform for the development of new machine learning techniques.

Action-Respecting Embedding

A map is a key component for a mobile robot. Maps at their core allow the robot to answer three questions: (1) where have I been? (2) where am I now? and (3) how do I get where I want to go? A huge body of robotics research assumes their existence, and another large body of research tries to build them. But building maps is time-consuming, manually intensive, and requires expert knowledge in the form of detailed models of the robot's motion and sensor apparatus. This project investigates how maps can be learned directly from the robot's own subjective experience of sensations and actions, without any models. A new algorithm has been developed; Action Respecting Embedding (ARE), inspired by kernel-based dimensionality-reduction techniques. ARE extracts a low dimensional representation of data that also respects the provided action labeling. The resulting subjective map explicitly encodes the robot's trajectory

(answering question one), and can be used for both planning (question three) and localization (question two). Although originally conceived in the context of mobile robots, ARE is a general technique for extracting representations from a sequence of observations and actions.

Graphical Models for Optimal Point Set Matching

Point set matching is a fundamental problem of computer vision where one seeks an optimal match between a template point set and a larger image point set. This year we developed the first efficient algorithm that is guaranteed to solve this problem exactly, even though, for decades, computer vision researchers have been using approximate "relaxation" methods that are not guaranteed to produce an optimal matching. We have found that we can solve this problem by taking a new approach that combines graphical probability models and the theory of rigid graphs. By formulating rigid graph (point set) matching as a problem of finding a maximum probability configuration in a graphical model, we have developed the first provable, efficient, and exact point set matching algorithm for computer vision.

OBJECTIVES FOR NEXT YEAR

A major focus in the upcoming year will continue to be on temporal-difference networks as a framework for grounding world knowledge in subjective experience. A paper on combining temporal-difference networks with abstraction will be submitted to the Conference on Neural Information Processing Systems in June. There are several further steps to be taken with regard to temporal-difference networks: the learning methods must be made more efficient, off-policy learning methods must be incorporated, methods for automatically discovering questions must be found, and generally more experience and intuition have to be obtained regarding their power and limitations. The near term objective is to develop a few implemented examples to the point where a strong case can be made for the possibility and strength of grounding knowledge in experience, and then to prepare a journal article laying out the fundamental ideas of this approach. Some of these implemented examples may be with robots.

Function approximation methods will also continue to be a focus of our research. A paper on the theory and practice of the off-policy learning of recognizers with linear function approximation will be prepared and submitted for publication, probably to the Conference on Neural Information Processing Systems. We will also be exploring methods where performance is similar to least-squares methods, but are of lower complexity and thus can be applied to larger problems. Methods for learning efficiently by de-correlating input signals will also be explored.

Work on the RL Toolkit over the next year will focus on benchmarks and inter-language integration. Such benchmarks are widely recognized as a pressing need in reinforcement learning, and we intend to take significant steps in this direction. We will continue to develop tools facilitating communication between software modules written in different languages. A second major release, RL Toolkit 2.0, is planned for next year. Further development of open pages and of the G graphics system are also envisaged.

One of the robotics projects planned for next year is in the new area of "any-team" cooperative robotics. We are planning on building an "any-team" robot for the RoboCup small-size league. The goal is a scaled-back version of pick-up soccer, where one robot will be added to an existing team of robots, replacing one of their teammates. The vast number of existing capable teams provides an excellent testbed. The robot will not only seek to determine its role within the team, it will also adapt its attempts to coordinate through the use of a previously developed play-based team coordination system. Evaluation will initially be modest, seeking for the team performance to be better than if that robot had been replaced with a stationary obstacle.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

The project holds weekly group meetings attended by all faculty team members.

Faculty Team Members

NAME	ROLE
Richard Sutton	Team leader and Principal Investigator Reinforcement learning and artificial intelligence
Michael Bowling	Principal Investigator Robotics, multi-agent systems, reinforcement learning
Dale Schuurmans	Principal Investigator, CRC II Chair Probabilistic methods in artificial intelligence, machine learning
Vadim Bulitko	Associated faculty Decision-making in artificial intelligence
Mark Ring	Visiting professor, Chapman University Continual learning, neural networks, sequence learning. Dr Ring participates half-time in RLAI research by special arrangement as part of a collaboration with researchers at the Universities of Rutgers, Michigan, and Massachusetts
Katsunari Shibata	Visiting professor, Oita University, Feb-August 2005 Reinforcement learning, neural networks

Postdoctoral Fellows

NAME	ROLE
Finnegan Southey	Machine learning, opponent modeling
Li Cheng	Bayesian image modeling
Tiberio Caetano	Structural pattern recognition
Yaakov Engel	Gaussian process reinforcement learning Hired, to begin in April 2005 Alberta Ingenuity postdoctoral fellowship
Martin Zinkevich	Minimal regret algorithms Hired, to begin Sept 2005
Relu Petrascu	Supervised by Schuurmans Factored Markov Decision Processes

PhD Students

NAME	SUPERVISOR	SCHOLARSHIP/NOTES
Tao Wang	Schuurmans/Bowling	
Dana Wilkinson	Schuurmans	University of Waterloo
Adam Milstein	Schuurmans	NSERC PGS University of Waterloo
Qin Wang	Schuurmans/Dekang Lin	iCORE, Provost Doctoral Entrance Award
David Silver	Sutton/Martin Mueller	FS Chia, AIF upcoming

NAME	SUPERVISOR	SCHOLARSHIP/NOTES
Yuhong Guo	Schuurmans/Russ Greiner	
Feng Jiao	Schuurmans	
Linli Xu	Schuurmans	
Daniel Lizotte	Schuurmans/Russ Greiner	NSERC, Killam/Steinhauer upcoming
Ali Ghodsi	Schuurmans/Brendan Frey	Ontario graduate scholarship University of Waterloo
Jiayuan Huang	Schuurmans	Summer internship Max Planck Institute

MSc Students

NAME	SUPERVISOR	SCHOLARSHIP/NOTES
Brian Tanner	Sutton	NSERC PGS-M, Killam, AIF
Peter McCracken	Bowling	NSERC, Jeffery R. Sampson Graduate Memorial Prize
Nolan Bard	Bowling	
Lihong Li	Bulitko	Graduated, now a PhD student at Rutgers University
Cosmin Paduraru	Sutton/Bulitko	iCORE
Eddie Rafols	Sutton	NSERC upcoming
Adam White	Sutton	NSERC upcoming
Alborz Geramifard	Sutton/Bowling	
Armita Kaboli	Bowling/Petr Musilek	ECE student
Anna Koop	Undergraduate/MSc	Will be MSc with AIF scholarship in fall
James Neufeld	Undergraduate/MSc	Will be MSc in fall

Other team members

NAME	ROLE	NOTES
Matt Stephure	Team leader, Segway and robot simulation projects	
Jason Roberts	Segway programming	
Adrien Melanson	Segway and robot simulation programming	
Stephanie Schaeffer	RL Toolkit programming	Part-time
Samantha Vincent	Aibo programming	
Wesley Lo	Programming, Action-Respecting Embedding	
Mark Lee	RL Toolkit and open pages programming	
Lori Troop	Administrative assistant	Part-time
Priyanka Pareek	Open pages programmer	Part-time

COLLABORATIONS

PARTICIPANTS	NATURE OF COLLABORATION
PROVINCIAL	
Alberta Ingenuity Center for Machine Learning	Sutton, Schuurmans, and Bowling are among the seven principle investigators for this center at the University of Alberta. AICML contributes substantially to the RLAI project, totaling approximately $100K for the reporting period
NATIONAL	
Doina Precup, McGill University	Joint research on algorithms for off policy learning, temporal abstraction. A grant proposal is being prepared for submission to NSERC
Yoshua Bengio, McGill University Hugh Chipman, University of Waterloo Christian Leger, University of Montréal William Welch,University of British Columbia Jim Ramsay, McGill University Mu Zhu, University of Waterloo	MITACS grant "Statistical Learning of Complex Data with Complex Distributions" to Schuurmans, Sutton, and the listed collaborators $170K/year, RLAI portion ~$25K
Jonathan Schaeffer, Robert Holte, Duane Szafron, and Michael Buro University of Alberta	NSERC Strategic Grant, "Intelligent Agents for Interactive Entertainment" to Bowling, Schuurmans, and the listed collaborators $195K/year, RLAI portion ~$30K
INTERNATIONAL	
Satinder Singh, University of Michigan	Joint research with Sutton on predictive state representations and temporal-difference networks, conducted primarily by video-conference
Peter Stone, University of Texas at Austin	Joint research with Sutton on applying reinforcement learning to RoboCup soccer
Michael Littman, Rutgers University Satinder Singh, University of Michigan Andrew Barto, University of Massachusetts	DARPA grant "Intrinsically Motivated Reinforcement Learning" to Sutton with the listed participants. This grant funds Mark Ring's participation in RLAI. $480K/year, RLAI portion ~$36K
Jim Kehoe, University of New South Wales, Australia	Joint research with Sutton and Neufeld on the relationship between reinforcement learning and learning in animals. Visits were exchanged in the spring and summer; work proceeded remotely through the reporting period.
Michael Littman, Rutgers University	Prof. Littman visited the RLAI group for six and a half weeks in summer 2004 for joint research on reinforcement learning and predictive state representations
Frederic Maire, Queensland University of Technology, Australia	Prof. Maire visited Bulitko for the month of November 2004 for joint research
Eric Wiewiora, University of California, San Diego	Wiewiora is a PhD student who visited the RLAI group for three weeks for joint research on predictive state representations
INDUSTRIAL	
Electronic Arts	Bowling and Rob Holte presented a machine learning tutorial at Tiburon studios in Florida
Syncrude Research Centre Ian Parsons et alia	Sutton (with Robert Holte and Bill Bridger) discussed possible applications of reinforcement learning with Syncrude scientists.
IBM, the Minister of Alberta for Innovation, the University of Alberta	After extensive negotiation, an IBM Centre for Advanced Studies was agreed to be established at the University of Alberta. RLAI team members played a role in this coup for Alberta by identifying research projects of joint interest between them and IBM researchers
Syncrude Research. Ltd, Centre for Intelligent Data-Mining at the U of A	Bulitko on machine learning for vision systems
Automated Vision Systems, Inc., Los Gatos, California	Bulitko discussed possible technology transfer for the machine learning for vision systems project.

Collaborative activities in the research community

NAME	CONFERENCE/JOURNAL/ACTIVITY	ROLE
Schuurmans	International Conference on Machine Learning	Program co-chair
Sutton	NIPS workshop on "Reinforcement Learning: Benchmarks and Bake-offs"	Co-organizer
Sutton	ICML workshop on "Predictive Representations of World Knowledge"	Co-organizer
Sutton	International Conference on Machine Learning	Area chair
Sutton	International Joint Conference on Autonomous Agents and Multi-Agent Systems	Area chair
Sutton	Neural Information Processing Systems Conference	Program committee
Sutton	Conference on Uncertainty in Artificial Intelligence	Program committee
Sutton	Int'l Joint Conference on Artificial Intelligence	Program committee
Sutton	IJCAI 2005 Workshop on "Planning and Learning in A Priori Unknown or Dynamic Domains"	Program committee
Sutton	AAAI Fall Symposium on "Real Life Reinforcement Learning"	Organizing committee
Schuurmans	Machine Learning Journal	Associate editor
Schuurmans	Journal of Machine Learning Research	Associate editor
Schuurmans	International Conference on Machine Learning	Area chair
Schuurmans	Conference on Uncertainty in Artificial Intelligence	Area chair
Bowling	Machine Learning Journal	Guest co-editor
Bowling	Int'l Conference on Intelligent Robots and Systems	Exhibition co-chair
Bowling	AAAI Fall Symposium on "Artificial Multi-Agent Learning"	Organizing committee
Bowling	AAAI workshop on "Multiagent Learning"	Organizing committee

Public outreach

EVENT	PARTICIPANT
Public lectures and demonstrations at the Odyssium's exhibit on robotics	Bowling, Sutton
Mentoring of Edmonton high school students	Bowling
Presentations at Edmonton elementary and high schools (4)	Bowling
Public lecture at the Edmonton centennial "Philosopher's Cafe"	Sutton
Participation in iCORE public debate on robot rights	Sutton
Press: Edmonton Journal, Folio, Vancouver Sun, A Channel TV	Bowling

FUNDING

In this fiscal year, Rich Sutton received a one time grant from CFI (~$112K) with a matching donation from the University of Alberta. Dr Sutton and his team also received a combined total of ~$177K from various NSERC grants for the year. Other funding for this year came from AIF ($100K in kind), DARPA ($36K), MITACS ($25K) and NCE (~$23K). Dale Schuurmans, a member of Sutton's team, holds a Tier 2 Canada Research Chair providing $100K per year.

PUBLICATIONS

APPEARED ARCHIVAL PUBLICATIONS

B. Browling, J. Bruce, M. Bowling, and M. Veloso, "STP: Skills, Tactics and Plays for Multi-robot Control in Adversarial Environments," *IEEE Journal of Systems and Control Engineering*, pages 33-52, 2005.

S. Wang, D. Schuurmans, F. Peng, and Y. Zhao, "Learning Mixture Models with the Regularized Maximum Entropy Principle," *IEEE Transactions on Neural Networks 15* (4): 903-916, July 2004.

J. Huang, F. Peng, A. An, and D. Schuurmans, "Dynamic Web Log Session Identification with Statistical Language Models," *Journal of the American Society for Information Science and Technology*, 2004, Vol. 55, No. 14, Pages 1290 –1303.

L. Xu, J. Neufeld, B. Larson, and D. Schuurmans, "Maximum Margin Clustering," in *Advances in Neural Information Processing Systems* 17 (NIPS), 2005, pages 1537 – 1544.

M. Bowling, "Convergence and No-regret in Multiagent Learning," in *Advances in Neural Information Processing Systems 17* (NIPS), 2005, pages 209 – 216.

R.S. Sutton and B. Tanner, "Temporal-difference Networks," in *Advances in Neural Information Processing Systems 17* (NIPS), 2005, pages 1377 – 1384.

I. Levner and V. Bulitko, "Machine Learning for Adaptive Image Interpretation," in *Proceedings of the National Conference on Artificial Intelligence*, 2004, pages 870 – 876.

ACCEPTED ARCHIVAL PUBLICATIONS

S. Wang, D. Schuurmans, F. Peng, and Y. Zhao, "Combining Statistical Language Models via the Latent Maximum Entropy Principle," to appear in *Machine Learning*.

P. Stone, R.S. Sutton, and G. Kuhlmann, "Reinforcement Learning for RoboCup-Soccer Keepaway," accepted for publication in *Adaptive Behavior*.

M. Bowling, A. Ghodsi, and D. Wilkinson, "Action Respecting Embedding," to appear in the *Proceedings of the 22nd International Conference on Machine Learning* (ICML), Bonn, Germany, August 7 – 11, 2005.

T. Wang, D. Lizotte, M. Bowling, and D.Schuurmans, "Bayesian Sparse Sampling for On-Line Reward Optimization," to appear in the *Proceedings of the 22nd International Conference on Machine Learning* (ICML), Bonn, Germany, August 7 – 11, 2005.

B. Tanner and R.S. Sutton, "Temporal-Difference Networks with Eligibility Traces," to appear in the *Proceedings of the 22nd International Conference on Machine Learning* (ICML), Bonn, Germany, August 7 – 11, 2005.

L. Cheng, F. Jiao, and D. Schuurmans, "Variational Bayesian Image Modeling," to appear in the *Proceedings of the 22nd International Conference on Machine Learning* (ICML), Bonn, Germany, August 7 – 11, 2005.

L. Xu, and D. Schuurmans, "Unsupervised and Semi-supervised Multi-class Support Vector Machines," to appear in the *Proceedings of the Twentieth National Conference on Artificial Intelligence* (AAAI), Pittsburgh, Pennsylvania, July 9 – 13, 2005.

M. Bowling and P. McCracken, "Coordination and Adaptation in Impromptu Teams," to appear in the *Proceedings of the Twentieth National Conference on Artificial Intelligence* (AAAI), Pittsburgh, Pennsylvania, July 9 – 13, 2005.

B. Tanner and R.S. Sutton, "Temporal-Difference Networks with History," to appear in the *Proceedings of the Nineteenth International Joint Conference on Artificial Intelligence* (IJCAI), Edinburgh, Scotland, July 30th – August 5th, 2005.

D. Wilkinson, M. Bowling, and A. Ghodsi, "Learning Subjective Representations for Planning," to appear in the *Proceedings of the Nineteenth International Joint Conference on Artificial Intelligence* (IJCAI), Edinburgh, Scotland, July 30th – August 5th, 2005.

C. Boutilier, R. Patrascu, P. Poupart, and D. Schuurmans, "Regret-based Utility Elicitation in Constraint-based Decision Problems," to appear in the *Proceedings of the Nineteenth International Joint Conference on Artificial Intelligence* (IJCAI), Edinburgh, Scotland, July 30th – August 5th, 2005.

D. Schuurmans, Y. Guo, and R. Greiner, "Learning Coordination Classifiers," to appear in the *Proceedings of the Nineteenth International Joint Conference on Artificial Intelligence* (IJCAI), Edinburgh, Scotland, July 30th – August 5th, 2005.

E.J. Rafols, M.B. Ring, R.S. Sutton, B. Tanner, "Using Predictive Representations to Improve Generalization in Reinforcement Learning," to appear in the *Proceedings of the Nineteenth International Joint Conference on Artificial Intelligence* (IJCAI), Edinburgh, Scotland, July 30th – August 5th, 2005.

A. Ghodsi, J. Huang, F. Southey, D. Schuurmans, "Tangent-Corrected Embedding," to appear in the *Proceedings of the IEEE International Conference on Computer Vision and Pattern Recognition* (CVPR), June 20 – 25, 2005.

SUBMITTED ARCHIVAL PUBLICATIONS

D. Schuurmans, "Constraint-based Optimization and Utility Elicitation using the Minimax Decision Criterion," submitted to *Decision Analysis Journal*.

B. Price and J. Roberts, "Exploration Envelopes: A new approach to Transfer from Simulator to the Real-World," submitted to the *22nd International Conference on Machine Learning* (ICML), 2005.

F. Southey, M. Bowling, B. Larson, C. Piccione, N. Burch, and D. Billings, "Bayes' Bluff: Opponent Modeling in Poker," submitted to the *Conference on Uncertainty in Artificial Intelligence* (UAI), 2005.

M. Bowling, D. Wilkinson, A. Ghodsi, and A. Milstein, "Subjective Localization with Action Respecting Embedding," submitted to Robotics: *Science and Systems*, 2005.

Q. Wang, D. Lin, and D. Schuurmans, "Improved Estimation for Unsupervised Part-of-Speech Tagging," submitted to the *Conference of the Association for Computational Linguistics* (ACL), 2005.

S. Wang, R. Greiner, D. Schuurmans, and S. Wang, "Consistency and Generalization Bounds for Maximum Entropy Density Estimation," submitted to the *Conference on Computational Learning Theory* (COLT), 2005.

Y. Guo, D. Wilkinson, and D. Schuurmans, "Maximum Margin Bayesian Networks," submitted to the *Conference on Uncertainty in Artificial Intelligence* (UAI), 2005.

OTHER CONTRIBUTIONS

A. Ghodsi, J. Huang, and D. Schuurmans, "Transformation-invariant embedding," in *Proceedings of the 8th European Conference on Computer Vision* (ECCV), pages 520 – 527, May 11 – 14, 2004, Prague, Czech Republic.

K. Shibata, "Discretization of Series of Communication Signals in Noisy Environment by Reinforcement Learning," in *Proceedings of the Seventh International Conference in Adaptive and Natural Computing Algorithms* (ICANNGA), 2005, pages 486-489, held in Coimbra, Portugal, Mar. 23, 2005

I. Levner, V. Bulitko and G. Lin, "Feature Extraction for Classification of Proteomic Mass Spectra: A Comparative Study," in *Feature Extraction, Foundations and Applications*. Springer Verlag, to appear.

G. Lee and V. Bulitko, "GAMM: Genetic Algorithms with Meta-Models for Vision," in *Proceedings of Genetic and Evolutionary Computation Conference* (GECCO). Washington, D.C.

G. Lee, V. Bulitko and I. Levner, "Automated Selection of Vision Operator Libraries with Evolutionary Algorithms," in *Proceedings of the Congress on Evolutionary Computing* (CEC), pages 1127 – 1134. Portland, Oregon.

S. Ishii, M. Shidara, and K. Shibata, "An Explanation of Emergence of Reward Expectancy Neurons Using Reinforcement Learning and Neural Net," to appear in the *Proceedings of the Fourteenth Annual Computational Neuroscience Meeting* (CNS), 2005.

D. Silver, "Cooperative Pathfinding," to appear in the *Proceedings of the 1st Conference on Artificial Intelligence and Interactive Digital Entertainment* (AIIDE), 2005.

I. Levner and V. Bulitko, "Comparison of Machine Learned Image Interpretation Systems in the Domain of Forestry," in *Proceedings of the IEEE Workshop on Applications of Computer Vision* (WACV), 2005, pages 421 – 426. Breckenridge, Colorado.

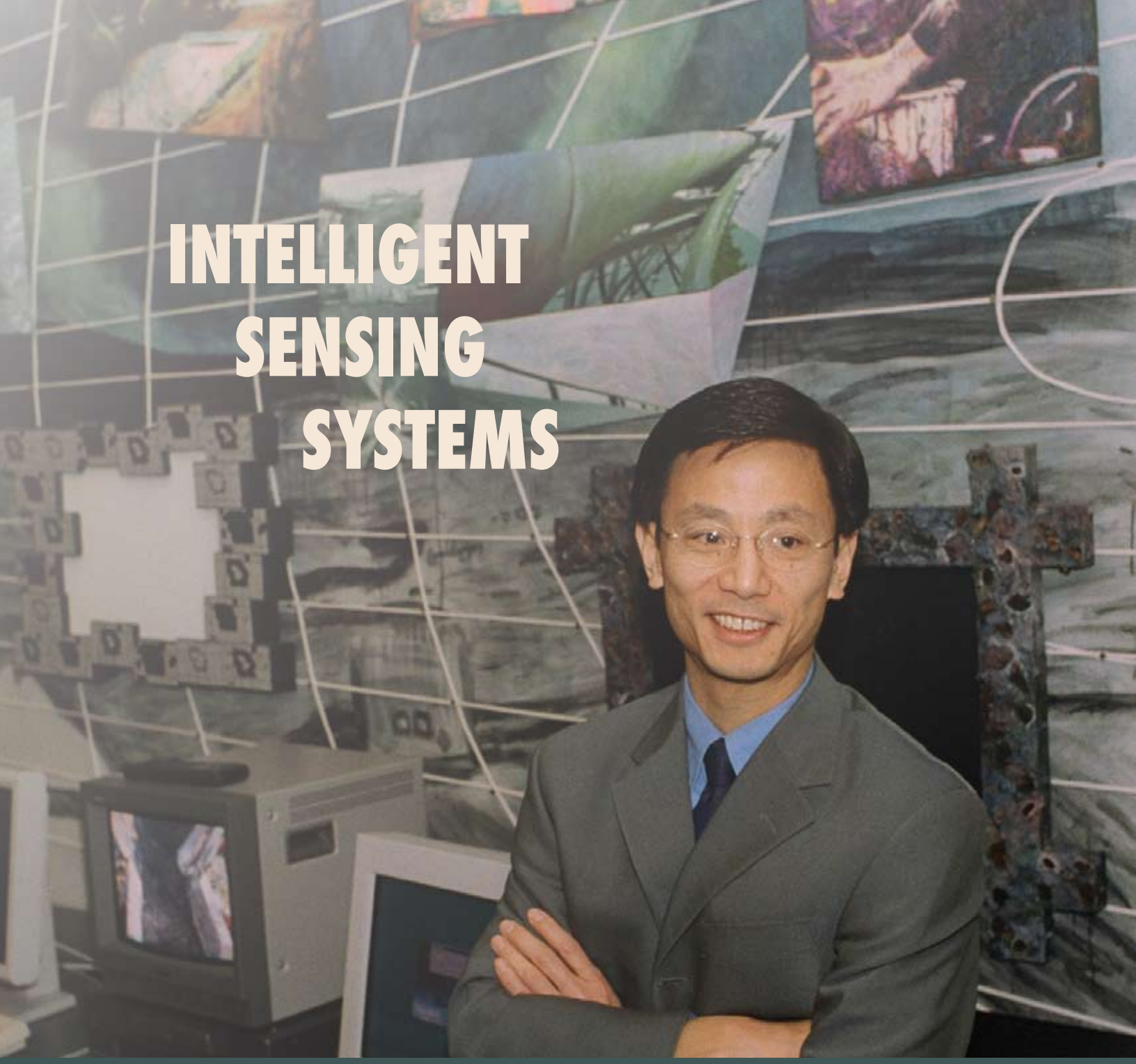
P. McCracken, and M. Bowling, "Safe Strategies for Agent Modeling in Games," *AAAI 2004 Fall Symposium on Artificial Multiagent Learning*, pages 103-110.

L. Li, V. Bulitko, and R. Greiner, "Focus of Attention in Sequential Decision Making," National Conference on *Artificial Intelligence (AAAI) Workshop on Learning and Planning in Markov Processes – Advances and Challenges, Poster Session*, San Jose, California, July 26, 2004.

L. Li, V. Bulitko, and R. Greiner, "Batch Reinforcement Learning with State Importance," in *Proceedings of the European Conference on Machine Learning, Poster Section*, Pisa, Italy, September 20 – 24, 2004, pages 566 – 568.

V. Bulitko, "Learning for Adaptive Real-time Search," Computer Science Research Repository (CoRR), 2004.

R.S. Sutton, "Knowledge Representation in TD Networks," invited talk at the workshop on *Learning and Planning in Markov Processes – Advances and Challenges* at AAAI 2004, the annual conference of the American Association for Artificial Intelligence (San Jose, CA).



INTELLIGENT SENSING SYSTEMS

The long-term direction of the Chair's research program is to push the scientific envelope of information and communications technologies and apply these technologies to optimizing the performance of oil sands mining operations.

HONG ZHANG

NSERC/ICE Syncrude/Matrikon Industrial Research Chair
Centre for Intelligent Mining Systems, University of Alberta
http://www.cs.ualberta.ca/~zhang/

This second annual report of the NSERC/iCORE Syncrude/Matrikon Industrial Research Chair research program will highlight the projects in fundamental research in intelligent sensing systems and the application of this research to the monitoring of oil sand mining operations, conducted in the Centre for Intelligent Mining Systems (CIMS) at the University of Alberta. The second year of the Chair's research has seen the assembly of the core research personnel and solid progress in several areas of importance.

EXECUTIVE SUMMARY

In the past year, we successfully recruited two research associates, one post-doctoral fellow, and three new graduate students, and graduated one MSc student. Our main basic research activities have focused on:

- A general framework based on wavelet analysis for oil sand image segmentation
- Adaptive image processing algorithms based on machine learning
- Adaptive color classification
- Steam detection
- Adaptive contrast enhancement

The main applied research activities in the past year have included:

- A fines model for oil sand particles
- Automated region of interest detection
- Rejects chute evaluation
- Modeling of comminution circuits
- The integration of CIMS ore size analysis system (Ore Size Analyst or OSA) with Matrikon's industrial software (ProcessMonitor), in preparation for its field trial

RESEARCH PROGRAM OVERVIEW

The long-term direction of the Chair's research program is to push the scientific envelope of information and communications technologies and apply these technologies to optimizing the performance of oil sands mining operations. We study sensor processing algorithms for monitoring the various stages of oil sands mining, where the research will lead to objective performance models of the mining components and the entire mining process. These performance models will enable the industry to improve the performance of its mining process by maximizing the throughput, while minimizing the rejects and the environmental impact.

A key performance indicator of the mining process is the size of the oil sand ore as it progresses through the ore sizing and delivery pipeline. On that basis, our research addresses two areas that are fundamental for objectively evaluating a mining process, focusing on ore size:

- Reliable sensor processing algorithms for ore size measurement under variable environmental conditions
- Statistical modeling of a system and its components with respect to their performance metrics.

In order to establish a comprehensive framework for the oil sand size analysis throughout the oil sand sizing process, we investigate the use of both gray-scale intensity images and range images, captured with stereo vision or laser range finder, as a more direct means of measuring oil sand size. We tune a multitude of image analysis techniques and algorithms that have proved their success in other domains, for our application. Our research is first developed in CIMS on scaled models of field equipment and streamed field sensory data (video or range), and then tested and fine-tuned at Syncrude's North Mine or Aurora Mine.

With respect to specific applications of the research developed within CIMS, in the early stage of research, after careful consultation with our industrial partner Syncrude, we have decided to focus our efforts on the particle size measurement of conveyed oil sand ore. An immediate benefit of the ability to measure the ore size on a conveyor belt is to allow Syncrude to effectively evaluate the efficiency of the screens that are deployed at several junctions in the oil sand sizing process to separate the large ore fragments from the small ones. Another benefit is to ensure that Syncrude will be able to objectively determine if their crushers do indeed reduce ore size according to their design specifications, and do not place unintended strains on the subsequent ore sizing and delivery operations.

RESEARCH PROJECTS

Adaptive Multi-scale Direct Contrast Enhancement

Analyzing oil-sand images is very challenging. Oil-sand ore comes in a variety of sizes, shapes, colors and textures and is most often mixed with dirt and fine particles. Varying lighting and weather conditions also play a significant role. The goal of this research is to improve the segmentation of oil-sand images through proper contrast enhancement as a necessary first step.

Our proposed contrast enhancement method is based on several assumptions. First of all, only a certain degree of enhancement is required, and both over enhancement and under enhancement are undesirable. To achieve this, we employ a contrast enhancement method that is direct, in which the amount of enhancement is controlled based on a contrast measure. Secondly, objects of different sizes in an image are best enhanced on their corresponding scales. To develop an algorithm capable of this, our proposed method is multi-scale in which the scale of enhancement is selected based on expected object size. Finally, since objects in different local areas are of different sizes, each local area requires a different degree of enhancement. Our method is spatially adaptive in which different local regions are enhanced differently.

Hong Zhang

Image Segmentation by Adaptive Thresholding and Gradient Watershed

Many images consist of distinctive regions with different characteristics. The segmentation of such images, therefore, calls for separate algorithms applied to different regions. Typical oil sand images contain coarse pieces and fine particles. The coarse pieces within the Region of Interest (ROI) are characterized by being relatively bright, while the fine particles between the coarse pieces collectively look like a texture. Each must be treated using different segmentation techniques.

Based on the different characteristics between the coarse fragments and fine particles, we have proposed a two-stage image segmentation method combining gradient watershed transform and adaptive thresholding. Since watershed segmentation is time-consuming and does not meet the real-time needs, we employ an image-retrieval-like approach to accelerate the size measurement of the fine particles.

To define a signature for the implementation of the image-retrieval-like solution, we employ wavelet analysis, which provides a multi-resolution and orientation representation of an image via subbands, consistent with the human visual system. Due to this characteristic of wavelet analysis, it has been used as an efficient tool for texture analysis. Various methods of wavelet-based texture characterization have been proposed, based on the statistical properties of intra-band. There are three typical wavelet texture signatures: Extended Energy (EE) signature, Generalized Gaussian Density (GGD) signature and Co-occurrence signature. Based on the ore fragmentation process, we propose in this paper a new wavelet signature: the Weibull signature. The experimental results show that the Weibull wavelet signature provides better performance than the existing wavelet signatures.

Optimization of Image Processing Parameters

In this project, we are interested in being able to determine the optimal parameter setting of an image processing algorithm, for a given image. In general, the performance of image processing algorithms is sensitive to parameter values such as thresholds and window size. A desired solution is to select image processing parameter values automatically on a per image basis.

To that end, we explore a solution based on an existing image interpretation system (MR ADORE). Our solution demonstrates a great potential of applying machine learning techniques to the ore size measurement domain. Experimental results show that the adaptive system outperforms its counterpart in which a constant set of parameter values are used independently of the images being processed.

We focus on the problem of oil sand image segmentation as a first step toward an adaptive parameter selection algorithm that can be applied to any image processing systems, which experience the problem of parameter selection. As our solution approach, we adopt MR ADORE as a machine-learning framework, supporting it with a new scoring metric, a set of feature extraction techniques, and a given sequence of image processing operators. We make use of a domain-independent approach in which a control policy over the space of vision operators is machine learned, and this represents an innovative application of Artificial Intelligence technology, which is supported with the empirical evaluation. Most importantly, the system is adaptable to other image processing applications.

Ore Size Analysis of Moving Oil Sand Particles

In this project, we develop a novel approach to estimate the 2D shapes of moving rejects, which combines adaptive Gaussian mixture model and optical flow methods in order to achieve robust and accurate extraction of moving objects in a static background. This image processing algorithm is useful for evaluating the efficiency of the screen at the rejects chute where particles unable to pass the screen holes are rejected. The algorithm works well for image sequences with many moving objects of different sizes. Extensive experimental results have been obtained on real image sequences to demonstrate the feasibility and the efficiency of the proposed technique.

Many approaches of segmentation of moving objects in image sequence have been proposed in the literature. They can be classified into temporal differencing, background subtraction and optical flow.

Our analysis of the three common segmentation methods reveals that temporal differencing is good at providing initial coarse motion areas. Background subtraction can provide the most complete feature data. Optical flow technique has an advantage at detecting movement or the velocities of objects from an image sequences. Our approach of using a combination of the data from these three different methods produces better results than any one of the three alone.

Some of Hong Zhang's research group on a visit to the Fort McMurray oil sand mine

Image Processing Algorithms for Steam Detection and Removal

Due to the use of hot water in the oil extraction process and because of the lower temperatures registered during most of the year in the mining sites in northern Alberta, presence of steam is an unavoidable factor which may affect considerably the performance of video image processing algorithms applied to computing the ore size distribution. In this context, detection and quantification of areas covered by steam is a very important task which can be used to determine if a video frame should be considered for analysis.

In this project, we attempt to develop a real-time image processing technique for detection of steam in oil sand video images. The problem of detecting steam in an oil sand video stream is treated as a supervised pattern recognition problem. We use a wavelet-based steam signature, especially designed for the purpose of characterization of the steam texture, as an input to a Support Vector Machine technique. By detecting and providing the total area covered by steam in a video frame, a computerized image processing system can automatically decide if the frame can be used for further analysis. The proposed method has been quantitatively evaluated by using a labeled image dataset sampled from real video frames.

Adaptive Color Classification

Color has been used in many computer vision applications, such as image segmentation, object tracking and recognition. The appearance of an image is affected by illumination so color-based vision applications have often faced the problem of colors being sensitive to illumination variation. A static color model can not handle illumination variation and so an adaptive color model was introduced to deal with dynamic illumination.

This project is motivated by the need for color classification in many practical applications. We developed an adaptive color classification algorithm that uses a two component Gaussian Mixture Model (GMM) to model a color distribution in YUV color space. The components of this model represent the diffuse and the specular parts of the dichromatic reflectance model. The GMM is derived from classified color pixels using the standard Expectation-Maximization (EM) algorithm, and the color model is repeatedly updated with the derived GMM. We propose the novel idea that a GMM with two Gaussian components is an accurate and complete representation of the color distribution of a dichromatic surface. This work is of practical significance because our adaptive system provides accurate color classification under variant lighting conditions and it outperforms the previous color vision system without adversely affecting efficiency.

OSA Integration with ProcessMonitor and ProcessNet

OSA calculates the size distribution of the ore fragments in each image it receives. The size data by itself is of limited value; however, useful information can be derived when size is combined with other process data. In this project, OSA has been integrated with Matrikon's software platforms to turn ore size data into practical information. A prototype has been built which combines the size distribution of ore fragments calculated by OSA with feed-rate data recorded in Syncrude's historian to automatically monitor the performance of sieving screens. At present, Syncrude does not have a way to continuously monitor the screen efficiency, and therefore no way to optimize the use of these screens.

Our OSA-based screen efficiency prototype is at present running in the CIMS lab. A camera at the Fort McMurray mine site streams live video through a fiber network to the CIMS lab in Edmonton. An image acquisition card in a standard PC computer grabs images from the video feed. These sampled images are presented to the OSA in which fast image processing algorithms are employed to segment the image and calculate size distribution statistics. The OSA process is extremely fast and can sample and segment the images at a rate of over three images per second on a standard PC (1.8 GHz Intel processor). Matrikon's ProcessMonitor software reads size data from OSA, as well as the feed rate data through the Internet from Syncrude's PI historian. The data is checked for validity, and screen efficiency is calculated. The results generated in ProcessMonitor are passed on to a ProcessNet server. ProcessNet organizes the information derived by ProcessMonitor into tables, graphs, and trend charts, along with images to produce and serve various web pages that contain information relevant to Syncrude.

Modeling of Comminution Circuits (Crushers and Screens)

Comminution circuits are used in mining to reduce dimensionally large raw ore to a size that can be used as a product. This is done mainly through the use of crushers, screens, conveyor belts, and ore bins. To ensure that the circuit is operating at its highest efficiency, simulation and optimization are essential. Through surveying and modeling of the circuit components, simulations can be validated and optimization procedures can be run so as to increase efficiency. With the increase in comminution circuit efficiency, energy and cost savings can be obtained or increased plant product output can be achieved to increase revenue. This research looks at the process of plant surveying and system modeling with a review of simulation and optimization methods which might be applicable to modeling the crushers and screens that are widely used in sizing oil sand ore.

OBJECTIVES FOR NEXT YEAR

We will maintain the momentum that has been obtained in the first year and a half of the Chair's research program and continue to strike a balance between basic research in information and communications technology and the applications of such research to oil sand mining. With respect to basic research, we will invest time and effort in formulating image segmentation algorithms that make use of multiple cues and spatial constraints in theoretically rigorous frameworks. In addition, we will expand our research in applying existing machine learning techniques to the optimization of image processing algorithms. With respect to the applications of our research, in addition to our development of ore size algorithms for conveyor belt and rejects chute, we will revisit the problem of large lump detection, which is known to cause production stoppage due to the jamming of crushers in winter seasons. To realize the practical value of our research, we will work with our industrial partners in an attempt to provide operation support to the mine operators by delivering objective performance measures.

Our approach to ore size analysis has been to interpret it as one of image segmentation. Existing segmentation algorithms mostly depend on a single cue, edge, intensity, or texture, for example. However, these systems are fragile because rarely is a single cue sufficiently characteristic to extract the exact shapes of complete ore fragments, and this leads to inaccuracies and at times failures of the algorithms. In the coming year, we will explore a different approach in which multiple cues are combined to label the pixels of an image for the segmentation of ore fragments. Our approach will be built on a Bayesian framework, with each cue contributing to the segmentation decision in terms of a probability of a pixel belonging to an ore fragment. In addition, we will apply the Markov Random Field (MRF) theory to impose spatial and temporal constraints in the interpretation of an image so that neighboring pixels are segmented jointly, possibly over a video sequence when applicable.

Another area of considerable interest to our research is the use of machine learning techniques for sensory data processing algorithms. Advances have been made in the field of machine learning in the past few years. In addition, there exists considerable strength at the University of Alberta in the area. We will take advantage of this strength in three different ways. First, we will continue our research in adaptively selecting image processing parameters with respect to a given image. Secondly, we will develop image processing algorithms that benefit from human image interpretation skills. Finally, we will develop techniques by which past experiences — both successes and failures — in image interpretation can direct how new similar images should be processed.

Crushers are used to reduce ore size and, due to the cold winter in Northern Alberta, crushers are jammed often as the result of large frozen lumps, interrupting the production pileline. Therefore, there is a pressing need to develop a technique to detect the presence of large lumps in the feed going into a crusher so that the crusher operator can be warned and take action to reduce the possibility of jamming. We have developed such a software based on analyzing a static image while ignoring the rich information present in a video sequence as a large lump travels through the conveying system. This new dimension of information will be utilized to improve the reliability of the large lump detection software.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

NAME	ROLE/TOPIC
Dr Hong Zhang	CIMS director/Chair holder
Dr Ron Kube	CIMS co-director/industrial partner from Syncrude
Dr Mark Polak	Lab Manager/industrial partner from Matrikon
Dr Martin Jagersand	Faculty member
Dr Dongxiang Zhou	Post-doctoral fellow
Dr Minghong Pi	Research associate
Dr Ricardo Ferrari	Research associate
Ilya Levner	PhD candidate
Xiang Wang	PhD candidate
John Sheldon	MSc candidate
Xiaoli Wang	MSc candidate
Andrzej Zadorozny	MSc candidate
Xiaohu Lu	MSc candidate
David Laing	Undergraduate student
Yury Potapovich	Undergraduate student/IIP student with Syncrude
Lizhen Wang	Visiting professor
Melanie Calvert	Administrative Assistant

FUNDING

Hong Zhang received ~$200K this year from NSERC to combine with his iCORE Industrial Chair ($150K) funding. He also recieves yearly funding from his industrial partners Syncrude ($100K) and Matrikon ($50K).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

"A Multistage Adaptive Thresholding Method", Feixiang Yan, Hong Zhang and C. Ronald Kube, *Pattern Recognition Letters,* Volume 26, Issue 8, June, 2005, pp. 1183-1191.

"Collective Robotic Site Preparation", Chris Parker and Hong Zhang, to appear in Adaptive Behavior.

REFEREED CONFERENCE PROCEEDINGS

"Toward Versatility of Multi-Robot Systems", Colin Cherry and Hong Zhang *3rd International NRL Workshop on Multi-Robot Systems*, March 14-16, 2005 Washington, D.C.

Collective Decision Making: A Biologically Inspired Approach to Making Up All of Your Minds", Chris Parker and Hong Zhang, in *Proc. of 2004 IEEE International Conference on Robotics and Biomimetics*, China, August 22-26, 2004.

"Biologically Inspired Decision Making for Collective Robotic Systems", Chris Parker and Hong Zhang, *Proc. 2004 IEEE International Conference on Intelligent Robots and Systems*, Sendai, Japan, September 28-October 2, 2004.

"Collective Sorting with Local Communication", Sean Verret, Hong Zhang, and Max Q.-H. Meng, *Proc. 2004 IEEE International Conference on Intelligent Robots and Systems*, Sendai, Japan, September 28-October 2, 2004.

"Characterization of Acuity Laser Rangefinder", Xiujuan Luo and Hong Zhang, *Eighth International Conference on Control, Automation, Robotics and Vision* (ICARCV 2004), December 6-9, 2004, Kunming, China.

COLLABORATIVE VIRTUAL ENVIRONMENTS

Collaborative Virtual Environments (CVE) are truly the next generation of human- computer interface. In CVE systems, large and small computer resources are connected via the Grid allowing virtual groups of scientists to interact and collaborate in real time with simulations, instruments, and large datasets as if they were in the same meeting room.

PIERRE BOULANGER

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The iCORE chair on Collaborative Virtual Environments was awarded on January 1rst, 2005. It was officially launched on March 15th 2005. The launch received significant interest from local and national media; the announcement made the front page of the Edmonton Journal.

EXECUTIVE SUMMARY

During the first five months, our team was busy establishing the Chair. Besides solving the numerous administrative problems that come with setting-up research accounts, most of the time was spent on making sure the hardware and software infrastructures were ready for the bulk research work that started in April. On the communication infrastructure side, an Access Grid (AG) room, similar to a design office, was built at TRLabs and is now operational. We also upgraded the VizRoom at the Department of Computing Science to be AG compatible. This is in addition to the AG room at the University of Alberta Computer Network Services (CNS); making three AG rooms available for testing various configurations of collaborative environments. This will allow us to rapidly experiment with various collaborative configurations and will also become a showcase of collaborative technologies.

We also reconfigured the network in the laboratory to be fully accessible with the WESTGRID 1Gb/s backbone, the CANARIE CA*net4 User Controlled Light Paths (UCLP) as well as the TRNet 10Gb/s experimental network. We also acquired multiple cameras, haptic interfaces, and display devices to be integrated in the lab environment. In particular, we were able to build a low cost stereo display using a similar design to the one built at The Banff Center ART lab last year.

On the software side, multiple copies of CATIA, an advanced CAD software used by industry, was acquired and configured to be integrated with the AG environment at the various nodes.

On the scientific side, at Super Computing 2005 in Pittsburg, we demonstrated an example of collaborative computational steering of an earth magneto simulation. This demonstration included the UofA simulation server/client technology, the AG, and SGI Vizserver software. The simulation ran on multiple WESTGRID computers and successfully demonstrated the power of collaborative visual steering for simulation to the grid computing community. In many ways, this was a first for the grid community and the presentation created a lot of interest in the US and in Europe. As a consequence of this demonstration, we were asked to make a similar demonstration in September of this technology at the prestigious iGrid 2005 conference in San Diego. Apart from technical demonstrations, we also started to work on computational steering of Computational Fluid Dynamic (CFD) using the recent release of OpenFOAM. This open source code is truly a parallel CFD code that will allow us to rapidly demonstrate the power of visual steering for a wind tunnel application. Results so far show that this code scales very well with the number of CPUs and is capable of producing results in the time and with the precision necessary for the real-time constraints of a virtual wind tunnel. One of our goals for next year is to integrate this CFD real-time simulation server/client technology as part of a collaborative design review environment using CATIA V5 and AG.

These technology demonstrations have received significant interest from various industrial partners such as HP Research in Palo Alto, IBM Canada, and SGI Canada. So far SGI Canada and HP Research have made commitments to invest in the chair. In addition to these large corporations contributions, two small Canadian CAD companies (InnovMetric and Creaform

3D) are investing over $60K in the Chair to create a demonstration of collaborative CAD review for some of their high-end customers such as Airbus and Boeing. As the Chair progresses, we are expecting further involvement of large and small corporations.

In addition to industrial funding, the Chair was also awarded $139K by NSERC for an equipment grant to acquire various video and networking equipment. The Chair, in partnership with the University of Ottawa and the University of Calgary, was also awarded two $1.5M CANARIE Advanced Research Project (ARP) grants. The grants will be used for the applications of CA*net4 user controlled light paths (UCLP) for remote medical training of ophthalmology residents between Ottawa and Edmonton, as well as the use of Visual Area Networking for collaborative simulation steering between Montreal, Toronto, Edmonton, Calgary, and Vancouver. These projects are an excellent complement to the activities of the Chair, allowing further leverage of the money invested by iCORE.

RESEARCH PROGRAM OVERVIEW

The advent of high-capacity storage devices, powerful computer workstations, and high-speed networks is enabling (both technically and economically) a variety of multimedia communications services. Applications in training, medicine, education, concurrent-engineering design, remote monitoring, travel, real estate, entertainment, banking, insurance, administration, and publishing/advertising have quickly emerged. These applications are characterized by large multimedia documents that have to be communicated with very short delays. Computer-controlled co-operative projects, whereby a group of users can jointly create, edit, view, and produce collaborative work with multimedia documents, characterize many current and future research activities.

Professor Pierre Boulanger at the 2005 Intelligent Software Systems Chair iCORE Launch

In many new multimedia technology systems, Virtual Reality is now being used to display a multitude of information in a form that can be easily interpreted, shared, and manipulated.

One of the hottest topics in Virtual Reality research is in the field of Collaborative Virtual Environments (CVE). The idea behind CVE is very simple; a simulated world runs on several computer systems, each running a compatible CVE application. The computers are connected over a network and people using those computers are able to interact and collaborate in real-time, sharing the same virtual world. Some tele-immersive CVE systems recognize the presence and movements of individuals and objects, process those images, and then project them in realistic, multiple, geographically-distributed virtual environments where individuals can interact with each other and with computer-generated models.

CVE systems raise a number of resource allocation problems, including high-speed networks, clusters of large computers, data storage distributed over a grid, and advanced visualization tools such as the University of Alberta VizRoom. The advent of grid computing/visualization facilities such as WestGrid provides fresh challenges and opportunities for collaborative visualization, including the close coupling of simulation, visualization, and Internet communication tools in a steering environment capable of creating the equivalent of a real-time physics experiment.

In some systems, CVE aims to enhance a video conferencing environment with access to visualization facilities. At the most basic level, pre-generated visualization may be shared through a shared whiteboard tool. In these systems, interactive change and exploration of the influence of simulation parameters is time-consuming and not very intuitive. Richer approaches enable users to share control of the visualization/simulation process allowing for true exploration of the simulation space. The main goal of this Chair is to conduct research and development on the various issues relating to implementation of CVE systems. The key scientific and technical challenges that have to be solved will require an expansion of the boundaries of computer vision, low latency networking, real-time tracking, stereo display, haptics, and real-time rendering technologies.

RESEARCH PROJECTS

On the research side the following projects will be the main focus of our activities for this year:

CVE for the Collaborative Visual Steering of Large Simulations using the WestGrid Infrastructure

The goal of this project is to explore how advanced technologies will allow scientists to collaborate with each other easily, efficiently, and effectively in the context of a computational physics simulation. More specifically, we will explore how to maximize the Quality of Experience (QoE) for the end user over a wide range of technology platforms. Critical to this work is the fact that QoE is a human-centered measure and not a technology-centered measure. Thus, we want to maximize the human perception based on a rich and diverse set of factors. These factors include, but are not limited to: networking (broadband, wired, and wireless), interaction (3D tracking, touch sensitive devices, voice recognition, mouse, keyboard), and display (immersive displays, wall, table top, desktop, laptop, tablet, PDA). Fundamental to this project is the creation of an architecture to support advanced collaborative environments. This architecture is an open one, allowing for the extensible creation of collaboration services and the ability to deploy those services on a wide range of heterogeneous technology platforms.

Hapto-Audio-Visual Environments for Collaborative Tele-Surgery Training over Photonic Networking (HAVE Project)

The goal of this project is to develop shared Hapto-Audio-Visual Environments (HAVE) with advanced multi-point 3D video conferencing, new display and interface technologies, and solution servers technologies that will be used for collaborative medical research and training. The expected result is the demonstration and evaluation of a realistic HAVE immersive collaborative virtual environment application for the training of ophthalmic residents in cataract surgery, linking the Virtual Reality CAVE systems at the University of Ottawa and University of Alberta through regional high-speed networks and CA*net4. This innovative project will create collaborative training environments in which residents can perform virtual cataract operations on real and virtual eyes using real/virtual surgical instruments, while receiving immediate sensory feedback from a haptic system that simulates real tissue resistance and facilitates the learning of proper hand-to-eye coordination. HAVE tele-surgery applications will enable junior residents to be trained by remote experts and deliver improved patient care and reductions in training costs and risks. The benefits to the community are to raise the profile of the bandwidth and networking capabilities of CA*net4 and the use of end-to-end User Controlled Light Paths necessary to meet the quality-of-service requirement of this demanding application.

Professor Pierre Boulanger and part of his research team at the 2005 Banff Informatics Summit

At this point, we are in the design phase of the project. We have had numerous meetings with our partners at the University of Ottawa, with doctors at the Ottawa Eye Institute, and with Dr Matt Tennant at the Department of Ophthalmology at the University of Alberta. Our aim is to capture current surgical practices and how cataract surgery is taught at various medical schools. Following best practice captures, a more precise technical specification of the project will be performed and various equipment and software will be acquired. This year, we were very fortunate to get a NSERC Equipment grant ($139K) to cover most of these hardware expenses.

Multi-Modal Interface for CVE Systems

In this project, we will investigate enriched interactive environments where multiple types of devices and technologies can be combined in novel ways for single and collaborative work and to explore simulation data in new ways. Several technologies are being combined and evaluated, from the leading edge to consumer products including PC-based passive stereo wall and table-mounted large touch-screen displays, high-resolution desktop systems, laptops, haptics interface, handheld trackers for sonification, pen-based computing tablets and even paper. The research goals for this project centre around the study of how heterogeneous devices may be combined into device suites for particular complex information tasks, and what tasks these suites and enriched environments may aid or impede. For the first phase of this project, we are planning to use 3D haptic devices to sonify and feel flow field resulting from simulations from the virtual wind tunnel simulations.

This year, a basic prototype of the haptic/sonification system for the real-time wind tunnel is under development. In this prototype, an interface between OpenFOAM and the UofA visualization client was created to display (in real-time) flow field transmitted by the simulation server. In addition, an interface between MAX/MP, sound synthesis software, and the visualization client is under development using a local area network based on Virtual Reality Peripheral Network (VRPN).

OBJECTIVES FOR NEXT YEAR

CVE for the Collaborative Visual Steering of Large Simulations using the WestGrid Infrastructure

This year we demonstrated that the current simulation server/client technology for the CFD simulation as well as for the earth magneto simulation is working well but suffers from numerous design problems. It is planned next year to redesign the simulation server using MPI instead of threads, and to optimize openFOAM to work in real-time. We are also planning to develop specialized functions in the client to deal with CFD results. We also aim to add more steering functionality such as the ability to change advanced boundary conditions (in real-time) and then integrate the CFD real-time simulation server/client technology as part of a collaborative design review using CATIA V5 and the Access Grid. We are also planning to demonstrate this technology at iGRID2006 and HPC 2006.

Hapto-Audio-Visual Environments for Collaborative Tele-Surgery Training over Photonic Networking (HAVE Project)

This year we captured the preliminary design specifications for the requirements of a cataract surgery trainer. We also produced a preliminary HAVE application design including a refined HAVE architecture for both graphics and haptics communications with a specific 3D teleconferencing system in mind. Next year, we aim at deploying a network infrastructure using CA*Net4 User Controlled Light Path. We are also planning to build a first prototype of the HAVE eye tele-surgery trainer, and test the system with ophthalmologists located in Ottawa and Edmonton. We are also planning to demonstrate this system to the annual CANARIE meetings and to publish the results in various peered reviewed journals.

Multi-Modal Interface for CVE Systems

Over the next year we aim to integrate haptic interface to a visual system. We will also aim to develop haptic and sound-rendering algorithms specialized for CFD data and then integrate sound and haptic together. We will study usability for various haptic, visual and auditory strategies in the context of CFD data analysis, and will endeavor to publish our results.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

TEAM LEADER	ROLE/TOPIC	AWARDS/SPECIAL INFO
Pierre Boulanger	System Architect	Financed by iCORE, NSERC, Canarie, ASRA

Project #1

FACULTY TEAM MEMBERS	ROLE/TOPIC	AWARDS/SPECIAL INFO
Manuel Garcia	CFD specialist/ Visiting Professor	ASRA
PHD CANDIDATES		
Irene Cheng	Geometric Compression	Paid by NSERC Operating
MSC CANDIDATES		
Maryia Kasakevich	Multi-Modal Interface	
OTHER TEAM MEMBERS		
Curtis Badke	Programmer	Programmers paid 50-50 by iCORE and CANARIE ARP program
Jeff Ryan	Programmer	
Brian Corrie	Interface with Westgrid	
Pablo Figueroa	Retargeting of VR Systems	
Dan St Germain	SGI Canada Associate	
Tom Malzbender	Tele-Immersion	
Maria Lantin	VR System Design	
Charles Mony	CAD Modeling	
Marc Soucy	CAD Modeling	

Project #2

FACULTY TEAM MEMBERS	ROLE/TOPIC	AWARDS/SPECIAL INFO
Janelle Harms	Networking	
Richard Levy	CANARIE Project Manager	
PHD CANDIDATES		
Baochun Bai	Multi-Video Server	NSERC, ASRA
MSC CANDIDATES		
Chris Ozeroff	System Integration	
Hector Padilla	Vision Algorithms	RA paid by CANARIE and iCORE
OTHER TEAM MEMBERS		FINANCED BY CANARIE
Trevor Hall	Canarie Project Manager	
Nicholas Geoganas	System Architect	
Matt Tennant	Ophthalmology consulting	
Tom Malzbender	HP Research Associate	
Brian Moore	BigBangWidth/Associate	

Project #3

FACULTY TEAM MEMBERS		
Walter Bischof	Usability Studies	
MSC CANDIDATES		
Maryia Kasakevich	Sonification + Haptic Implementation	iCORE Chair Funded
OTHER TEAM MEMBERS		
M. Lantin	VR Systems	
P. Bourdot	Multi-Model Systems	
P. Figueroa	Re-targeting of VR systems	

COLLABORATIONS

PARTICIPANTS	NATURE OF COLLABORATION
PROVINCIAL	
Maria Lantin/ Banff Centre	VR Display Specialist
Walter Bischof/Department of Computing Science	Usability Studies Consulting
Matt Tennant/ Faculty of Medicine	Ophthalmology Consulting
Carlos Lange/ Department of Mechanical Engineering	CFD Specialist
Janelle Harms	Network Specialist
Richard Levy/ University of Calgary	User Interface Specialist
NATIONAL	
Trevor Hall/ University of Ottawa	HAVE Project Manager
Nicholas Geoganas/ University of Ottawa	HAVE Project Main Achitect
Brian Corrie/ SFU+WESTGRID	Visualization Specialist
INTERNATIONAL	
Patrick Bourdot / CNRS France	Multimodal Interface Specialist
Pablo Figeuroa/ University of Los Andes, Colombia	Retargeting and Multimodal Interface Specialist
Manuel Garcia/ University of EAFIT, Colombia	CFD Specialist
INDUSTRIAL	
Dan StGermain/ SGI Canada	SGI Consulting
Tom Malzbender/HP Associates	Immersive Video Conferencing Specialist
Charles Mony/ Creaform3D	CAD Consulting
Marc Soucy/ Innovmetric	CAD Consulting

FUNDING

Pierre Boulanger is a new iCORE Industry Chair. iCORE contributes $50K per year and Professor Boulanger recieved a matching $50K contribution from TRLabs. In the next fiscal year the chair will also receive an extra $100K per year from SGI Canada and a one year investment of $50K from InnovMetric.

PUBLICATIONS

PEER REVIEWED JOURNAL

P. Figueroa, W.F.Bischof, P. Boulanger, J.Hoover, "Efficient Comparison of Platform Alternatives in Interactive Virtual Reality Applications", *Int. J. Human-Computer Studies 62*, 2005, pp. 73–103.

I. Cheng and P. Boulanger, "Feature Extraction on 3D TexMesh Using Scale-space Analysis and Perceptual Evaluation," *IEEE Transactions on Circuits and Systems for Video Technology, Special Issue October 2005*, vol. 15, no. 10, pp. 1234-1244.

I. Cheng and P. Boulanger, "Adaptive Online Transmission of 3D TexMesh Using Scale-space and Visual Perception analysis," *IEEE Transactions on Multimedia, 2005* (in press) Accepted May 11, 29 Pages.

PEER REVIEWED CONFERENCES

I. Cheng and P. Boulanger, "A 3D Perceptual Metric using Just-Noticeable-Difference," *EUROGRAPHICS 2005 Dublin*, Short Paper, pp. 97-100. Acceptance rate 30 percent.

I. Cheng and P. Boulanger, "A Visual Quality Prediction Model for 3D Texture," EUROGRAPHICS 2005 Dublin, Short Paper, pp. 101-104.

I. Cheng and P. Boulanger, "Automatic Selection of Level-of-Detail based on Just-Noticeable-Difference," *SIGGRAPH 2005 Poster Session*, Los Angeles, California, USA, July 31, 2005, Poster 0104.

I. Cheng and P. Boulanger, "Adaptive Online Transmission of 3D TexMesh Using Scale-Space Analysis", *The second International Symposium on 3D Data Processing, Visualization, and Transmission* (3DPVT), Held in the city of Thessaloniki, Greece, September 6 to 9, 2004, pp. 688-695.

G. Osorio, P. Boulanger, and F. Prieto, "An Experimental Comparison of a Hierarchical Range Image Segmentation Algorithm", *18th Canadian Conference on Artificial Intelligence Graphics Interface 2005 2nd Canadian Conference on Computer and Robot Vision* in Victoria BC, May 8-11, 2005, pp. 571-578.

P. Boulanger, "From High Precision Color 3D Scanning of Cultural Artifacts to its Secure Delivery Over the WEB: A Continuum of Technologies", *Workshop on "Recording, Modeling and Visualization of Cultural Heritage* in Ascona Switzerland May 22-26, 2005. On invitation only, electronic publication will be published in a book in 2005-2006.

M. Garcia, O. Ruiz, M. Gomez, and P. Boulanger. ''Spring Particle Model for Hyper-elastic Cloth''. *Canadian Congress on Applied Mechanics*, McGill University, Montreal, 29 May to 2 June 2005, pp. 141-142.

R. Taylor, D. Torres, and P. Boulanger, "Using Music to Interact With a Virtual Character", *5th International Conference on New Interface for Musical Expression*, Vancouver, Canada, May 26-28, 2005, pp. 220-223.

R. Taylor, P. Boulanger, and D. Torres, "Visualizing Emotion in Musical Performance Using a Virtual Character", *5th International Symposium on Smart Graphics*, Munich, Germany, August 22-25 2005, pp. 13-24.

P. Boulanger, G. Osorio, F. Prieto, "Hierarchical Segmentation of Range Images With Contour Constraints", The 5th International Conference on 3-D Digital Imaging and Modeling, Ottawa, Ontario Canada, June 13-16, 2005, pp. 278 - 284.

B. Bai, P. Boulanger and J. Harms, "An Efficient Multiview Video Compression Scheme", ICME 2005, *IEEE International Conference on Multimedia & Expo*, Amsterdam, The Netherlands, July 6-8, 2005. pp. 562-566.

PRESENTATION BASED ON ABSTRACT

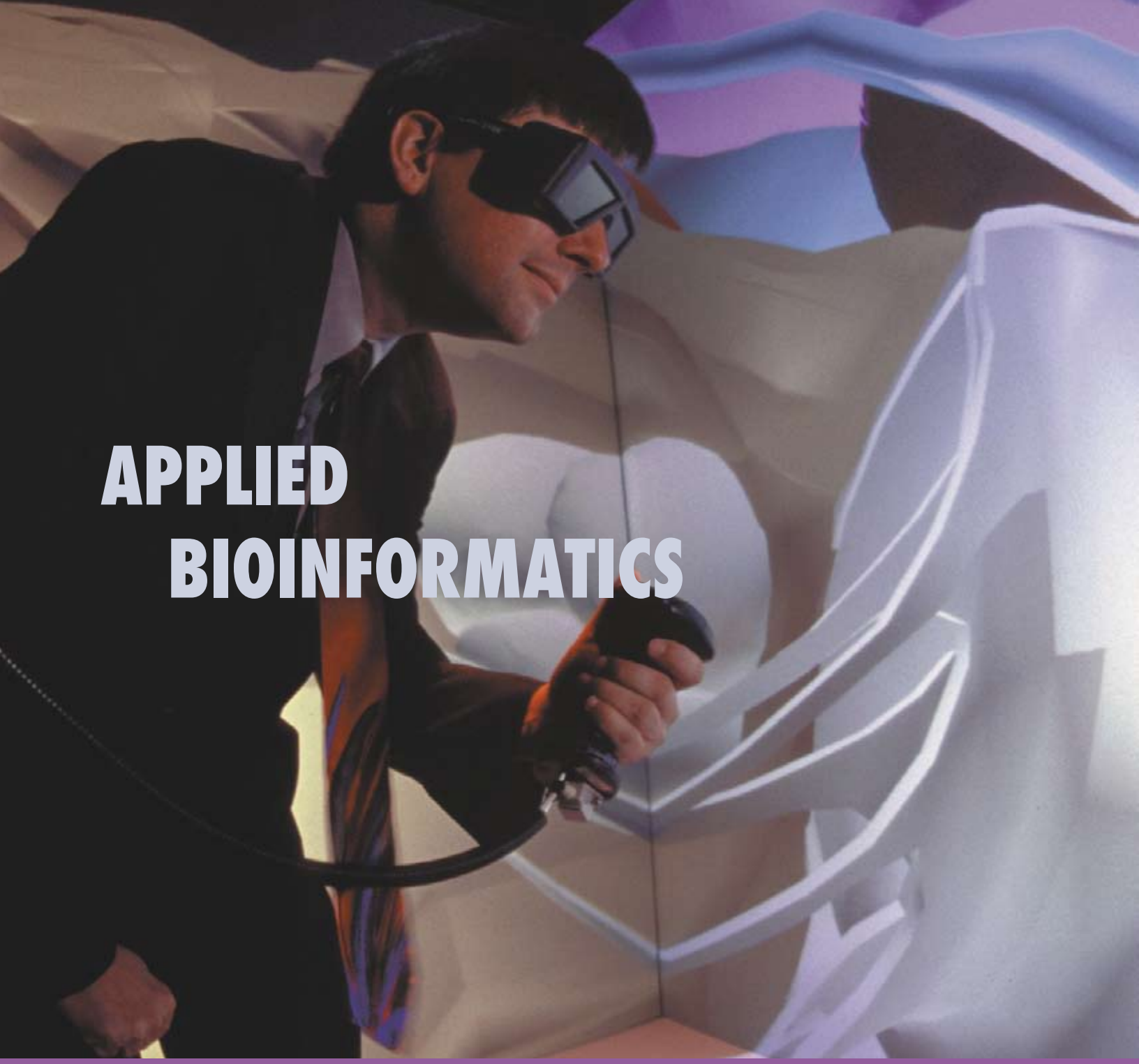
Pierre Boulanger. *Manufacturing and Collaborative Environments, Symposium on Virtual Reality and Visualization In Human Performance and Wellness*, March 22, 2005, University of Calgary, Calgary Alberta.

Pierre Boulanger, *From Computational Biomolecular Design to the Virtual Exploration of the Genome: A State- of-the-Art of the link between Visualization and Simulation for Bioinformatics*. WestGrid Summit, Monday April 18 – Wednesday, April 20, 2005, Banff, Alberta.

Pierre Boulanger. *Collaborative Virtual Manufacturing from the Ground Up*, BCNet 2005 Conference, April 25-27 2005, Vancouver, BC.

Pierre Boulanger. The HAVE Project: *Remote Surgical Training Over Advanced High-Speed Networks*, BCNet 2005 Conference, April 25-27 2005, Vancouver, BC.

Pierre Boulanger (Invited Speaker). *Virtual Reality: A New Tool for Rehabilitation, First Conference on Virtual Rehabilitation: Visioning the Art of the Possible*, May 27th 2005, At the University of Alberta, Edmonton Alberta.



APPLIED BIOINFORMATICS

We believe that growing interest in biological data integration and visualization, as evidenced by the growing number of scientific publications, will soon lead other research teams to the idea of merging advanced medical imaging data with gene expression data and other information.

Photographed by Maja Swannie

CHRISTOPH W. SENSEN

iCORE/Sun Microsystems Chair in Applied Bioinformatics
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The goal of the Applied Bioinformatics laboratory is to build the next generation of bioinformatics tools for data exploration, information integration, and advanced 4D visualization. We believe that the diverse set of large-scale data currently produced by genome research efforts needs new data integration approaches to reveal their full potential. At the same time, our development will also seek innovative solutions to several other underlying technical challenges: achieving a high degree of usability through fully visual and fully portable interaction; achieving scalability of the visualization through the use of semantic zoom and level-of-detail management; meeting security provisions and achieving platform-independence.

EXECUTIVE SUMMARY

We are working in two general directions: creating the computational environment for next-generation bioinformatics in collaboration with computer scientists, mathematicians and industrial partners (this is the main topic of the iCORE/Sun Microsystems activity); and creating models of biological systems in collaboration with clinical and wet-lab researchers. The users of the newly developed tools include life science researchers, both at the University of Calgary and other institutions, as well as students and trainees whose work involves data exploration.

Our iCORE/Sun Microsystems Chair program began in January 2005. Since then, we have made efforts to prepare a solid foundation on which to base our proposed five-year work plan. This involves both the infrastructure and the methodology for 4D data mapping.

In collaboration with Kasterstener Inc. from Red Deer, Alberta, we are currently in the process of building a virtual human body using Java 3D™. The human body model is not only anatomically correct but will enable the display of additional biochemical and biomedical data on the model in the future. This work will create a 4D spatio-temporal immersive platform for some of the key parts of our subsequent iCORE/Sun Chair research and development. Our research, although novel both in its 4D strategy and in the advanced technological tools it will deliver, is rooted in our deep knowledge of visualization techniques of 2D bioinformatics. We therefore have invested time in perfecting the genomic data mapping approach in 2D visualization, using the Bluejay genomic browser developed in our lab as a test case. We are now building middleware tools for the Java 3D™ immersive environment, which allow us to map medical data and genomic data onto the 4D anatomical model.

RESEARCH PROGRAM OVERVIEW

The Applied Bioinformatics laboratory has two major research themes, which often overlap: the development of 2D Bioinformatics tools and the development of 4D Bioinformatics tools.

The 2D Bioinformatics research theme is mainly focused on the integration of tools for the analysis and annotation of genomic data, including partial and complete genomes, as well as enhanced sequence tags (EST) and protein sequences. The major tools that we have developed thus far are called MAGPIE and Bluejay. In addition, we have developed a new approach to the identification of optimal oligonucleotides for a variety of experiments, including DNA sequencing and the design of gene chips, which was published in NAR in 2004. While most of the 2D Bioinformatics research is funded by Genome Canada with a view that the tools developed can be utilized by the other Genome Canada-funded research programs, some of the approaches that we develop here can also be utilized for the iCORE/Sun Microsystems related research endeavor. This includes our strategies for

visual data integration, semantic zooming through complex and large data collections, our approaches to the level of detail management, and some of our visualization strategies.

The iCORE/Sun Microsystems work is focused on the development of 4D Bioinformatics tools. The idea of merging anatomical imaging data and gene expression data to create a visual exploration environment is not especially new. Several research teams are currently developing similar projects, such as the Mouse Atlas Project at the University of California. At this moment though, we are not aware of any effort, which tries to establish a generic approach to the study of phenomena such as development, or complex genetic diseases, using an advanced visualization environment. We believe that growing interest in biological data integration and visualization, as evidenced by the growing number of scientific publications, will soon lead other research teams to the idea of merging advanced medical imaging data with gene expression data and other information.

The availability of the Java-enabled CAVE exploration environment and our emphasis on open standards and software interoperability will allow us to assemble a working prototype of the exploratory test bed using state of the art visualization and data mining tools. We are often utilizing pre-existing software packages for the main data-intensive parts of the process and use our own in-house development to fuse these parts together. Once the system prototype is operational, we will assess the capabilities, performance, and long-term prospects of using each of the components in collaboration with users from the particular medical community.

Christoph Sensen assisting Nicole in the CAVE

Tere Mahoney Photography

Our emphasis is on developing adequate technical capabilities to produce a coherent, versatile and user-friendly technological platform. As the system evolves and its usability is evaluated by medical researchers, we shall gain a better understanding of which specific patterns, ideas, or aspects of genetic diseases we should focus on. At present, however, we are concentrating our efforts mainly on the technological aspects of the development such as the implementation of strategies and algorithms for data processing, information fusion, and visualization.

Our overall research program plan is summarized as follows:

- Build up on our visual data integration know-how in 2D Bioinformatics
- Develop novel methodology for visual data integration in 4D Bioinformatics so that anatomical data and molecular-level data can be jointly explored
- Develop novel techniques to provide 4D scalability to very large datasets
- Create a functional 4D exploratory platform for genetic disease studies, such as brain cancer studies, based on the newly developed techniques
- Have alpha- and beta-users from the biomedical community evaluate thoroughly the usability of the new methodology and infrastructure

iCORE/Sun Microsystems-related Research Projects

Our iCORE/Sun Microsystems Chair program began in January 2005. Since then, we have been working on laying a solid foundation for the next several years of research and development. Using advanced imaging and genome research, we are proposing to make an attempt to better understand the mechanisms of genetic diseases. The main goal of our project is to merge a large number of diverse data types into coherent models. Using the CAVE automated virtual reality environment, we will allow users to interact with four-dimensional representations of the models in a natural way.

To achieve this objective, innovative solutions will be developed for several underlying technical challenges. This will include: finding the techniques for runtime data mapping, including remote grid-based mapping; developing a visual query mechanism that is fully portable across operating systems, visualization environments and devices; developing level-of-details management and semantic zoom for the virtual reality systems; and enabling a range of security provisions.

Our focus at present is on the development of the technical capabilities that will constitute the proposed research test bed. This test bed will allow the users to visualize data and models related to studies such as brain tumor research, to observe interesting patterns, formulate new ideas and hypotheses, and test them with advanced data analysis tools. The immediate availability of massive amounts of diverse data and cross-referenced data, a range of analysis tools, and query support over the entire data space will enable the researchers to analyze novel scenarios that are currently unavailable or require excessive efforts to simulate. The evolution of the system over the years will be guided in large part by the feedback from the users to reflect their needs and expectations.

We are collaborating with Kasterstener Inc. (Red Deer, AB), with the goal to build a virtual human body using Java 3D™. This work, funded by the Western Economic Partnership Agreement (WEPA), will be the basis for many of our tasks in the iCORE/Sun Chair program. The human body model will serve as a 4D platform for mapping genomic and molecular-level data onto anatomical imagery, providing a context for the subsequent studies of genetic disease. We have also continued to explore data mapping techniques in 2D, using the Bluejay genomic browser developed in our lab as a test case.

Much emphasis is put on developing a platform-independent system, which can be used on a large number of computational platforms. While the system will benefit from high-end computational resources, such as a high-performance computing environment, it will only unfold its full potential if it can be used (with some restrictions) on more generic environments. Our work on JABIRU system (Stromer and others, 2005) has made an important headway in this direction.

OBJECTIVES FOR THE NEXT YEAR

Our long-term research and development plan will proceed in four main stages over several years:

Initially, we will collaborate with Sun Microsystems, to implement a 3D visual GRID system based on SunRay technology, then development of a prototype system for the new 4D data exploration approach and creation of the features that make the system scalable to very large datasets. We will then aim to enhance the system's scalability to complex data operations and queries and implement personalized usability, security and decision support features.

In the coming year, our work will concentrate on stage one of our overall plan;. completing the computational hardware platform and creating a functional prototype of the new 4D data exploration system. This is a crucial period, in which the foundation will be laid for the subsequent efforts.

Our current laboratory workstations are SunRay 1 thin clients - approximately 100. Thus far, we have only been able to execute 2D applications in real time on the thin clients. We are now implementing a new experimental hardware and software solution by Sun

Christoph Sensen with some research team members at the 2005 Banff Informatics Summit

Microsystems as a beta test site, which allows us to use 3D applications in real time on the SunRay thin clients. This will greatly enhance our CAVE-related software development.

We are working with our partner Sun Microsystems on further enhancements of the computational infrastructure. It is our goal to provide access to our tools via Sun GRIDengine and BioMOBY Web services.

The work on the Java 3D™-enabled human body will start with a necessary preparatory and planning period, tentatively over the summer months of 2005. We will mobilize our existing strengths and expertise in visualization to streamline our approach for the new 4D visualization tasks. The existing infrastructure, methodology and software will be thoroughly assessed as to their fit for the upcoming technical challenges. Plans for the iCORE/Sun Chair development will be aligned with existing projects, such as the collaboration with Kasterstener Inc. in creating a Java 3D™ virtual human body. New personnel will be hired, using both the iCORE/Sun Chair funds and other project funds. The detailed plans for system architecture, design, and user requirements will be finalized. Alpha-users will be recruited from the biomedical community to provide an early and frequent feedback on the usability of the prototype, and to make practical suggestions.

Once the main strategic planning is finalized, there will be two main sets of tasks that we will need to accomplish. The first set of tasks is to develop adequate 4D image handling. The second set of tasks is to develop integration of genomics data. Our work will therefore begin in a two-pronged approach. We will designate two sub-groups of personnel, each led by a postdoctoral researcher, to work on the respective sets of task in parallel. Their efforts will converge at the end of Stage One, resulting in a functioning alpha-version prototype of the new 4D data mapping and exploration system.

The first set of tasks will involve making our Java 3D™ visualization infrastructure capable of handling and merging a diverse range of 3D imaging data. The imaging team will have two deliverables, each lasting approximately six months.

- As a first deliverable, a range of commonly used biomedical volume-based models, such as MRI, fMRI, CT or PET scans, should be easily visualized in our Java 3D™ CAVE. This involves primarily the ability to visualize volumetric data in Java 3D™, and the ability to merge diverse imaging data. We have already developed a Java 3D™ middleware system called JABIRU (Stromer and others, 2005) that provides several important portability and runtime interactivity features to Java 3D™ applications. JABIRU is still in a pilot stage and has been applied primarily to 3D surface models. It is based in part on an active manipulation of the Java 3D™ scene graph. Because volumetric models are typically much larger than surface models, and are structured differently, we will need to expand the JABIRU prototype considerably to accommodate volumetric data handling.
- As a second deliverable, the imaging team will implement image registration;. the ability of multiple image modalities to be aligned and merged into a single image. For example, this involves merging a patient's 3D MRI scan with a PET scan to infer a consensus location of a tumor, and then warping the image onto the human brain atlas. The team will utilize existing image registration algorithms and methodologies, and adopt them to the needs of Java 3D™ CAVE visualization. Image warping will use the human brain atlas developed collaboratively with the Kasterstener Inc.

The second group of tasks will involve the integration of genomics data and analyses into the Java 3D™ visual models. The genomics team, working in parallel and in cooperation with the imaging team, will have two deliverables as well, each lasting approximately six months:

- The first deliverable is to create the mechanism of positioning non-image genomics data, such as gene expression data, onto anatomical image models in 3D. This involves creating new Java 3D™ scene graph nodes internally when the user loads non-image data, "hooking" them to the correct locations in the overall scene graph, and ensuring their interactive behaviors as parts of the overall Java 3D visual model.
- The second deliverable is to add genomic data analysis features by integrating the TIGR MeV toolkit into the system. We have already accomplished a similar task in our 2D Bioinformatics efforts for the Bluejay genomic browser. Accomplishing this in a 4D environment will present several new challenges, especially in the creation of the 4D graphical user interface for launching the analyses interactively from within the CAVE environment.

The work of the two teams will converge in a functioning system prototype, and will be followed by a rigorous evaluation period. Thus, the next year will end by preparing the stage one completion and evaluations. Special emphasis will be placed on recruiting early biomedical alpha-users of the system, and soliciting their feedback for corrections and enhancements during stage two.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

NAME	ROLE/TOPIC
Dr. Andrei Turinsky	Postdoctoral Fellow 4D Bioinformatics effort team leader and GRID project team leader
Julie Stromer	MSc student 4D Bioinformatics middleware and volumetric data handling
Paul Gordon	PhD student 2D Bioinformatics effort team leader
Emily Xu	Programmer 2D Bioinformatics support programmer
Anguo Dong	NSERC Master's student 2D Bioinformatics comparative genomics project
Andrew Ah-Seng	BHSc student 2D Bioinformatics gene chip programming
Morgan Taschuk	BHSc student 2D Bioinformatics user interface programming
Chunyan Wang	Programmer GRID effortv
Jackie Irwin	Laboratory Technician (gene chip wet lab)
Kathy Laszlo	UNIX administrator
Ariane Mather	UNIX administrator
Trent Phillips	UNIX administrator
Julia Trangeled	Administrative Assistant
Marianne Hang	Genome Canada Project Manager
Sophie Chung	Genome Canada Training Coordinator and part-time Administrative Assistant
Irene Li (2004)	Master's of Biotechnology program
N.N.	iCORE/Sun Microsystems Postdoctoral Fellow
6 more positions open in recently started projects (WEPA and Genome Canada)	

COLLABORATIONS

iCORE/SUN MICROSYSTEMS CHAIR-RELATED COLLABORATIONS
Several research projects with Sun Microsystems, around Graphics, GRID and large-scale storage solutions
WEPA interactions with Kasterstener Inc. in Red Deer, Alberta on the completion of the virtual human body

INTELLECTUAL PROPERTY

Using WEPA funding, we have just secured the exclusive, perpetual right to using the Java 3D™ version of the Kasterstener Realism body for medical R&D in virtual reality environments. The WEPA project provides us with a foundation for much of the work projected under the iCORE/Sun Microsystems program.

FUNDING

Christoph Sensen a new iCORE Industrial Chair, has received a large amount of funding from Genome Canada (~$1.1M) this year as well as contributions from Western Economic Diversification Canada ($325K), CFI (~$343K), ASRA (~$40K) and NSERC (~$14K). He also receives a yearly cash contribution ($100K) from his industrial partner, Sun Microsystems of Canada, to match the funds given to him by iCORE.

PUBLICATIONS

PEER REVIEWED JOURNAL PAPERS:

B. Siebers, B. Tjaden, K. Michalke, C. Dörr, H. Ahmed, M. Zaparty, P. Gordon, C.W. Sensen, A. Zibat, H.-P. Klenk, S.C. Schuster, R. Hensel, "Reconstruction of the Central Carbohydrate Metabolism of Thermoproteus tenax by Use of Genomic and Biochemical Data". *J Bacteriol.* Vol. 186, 2004, pp. 2179-2194.

A.L. Turinsky, A.C. Ah-Seng, P.M.K. Gordon, J.N. Stromer, M.L. Taschuk, E.W. Xu, C.W. Sensen, "Bioinformatics Visualization and Integration with Open Standards: The Bluejay Genomic Browser." *In Silico Biol.* Vol. 5, 2004, p. 0018.

P.M.K. Gordon, C.W. Sensen, "Osprey: A comprehensive tool employing novel methods for the design of oligonucleotides for DNA sequencing and microarrays.: Nucleic Acids Research Vol. 29, 2004, e133.

G.H.Y. He, C.C. Helbing, M.J. Wagner, C.W. Sensen, K. Rabiowol, "Phylogenetic analysis of the ING family of PHD finger proteins." *Molecular Biology and Evolution* Vol. 22, 2005, pp. 104-116.

J.N. Stromer, G.T. Quon, P.M.K. Gordon, A.L. Turinsky, C.W. Sensen, "JABIRU: Harnessing Java 3D Behaviours for Device and Display Portability." *IEEE Computer Graphics & Application* Vol. 25, 2005, pp. 70-80.

PEER REVIEWED CONFERENCE PROCEEDINGS:

P.M.K. Gordon, J. Stromer, A.L. Turinsky, E. Xu, C.W. Sensen C.W., "Bluejay: A Biologcial Sequence Browser featuring Knowledge Integration. " Proceedings of the Fourth Virtual Conference on Genomics and Bioinformatics Vol. 3, 2004, pp. 4-11.

Y. Pan, C.W. Sensen, "Modular Neural Networks and their Application in Exon Prediction." *Advances in Bioinformatics and its Applications. World Scientific Publishing Co.*, 2005 (in press).

BOOK CHAPTERS:

A. Turinsky, P. Gordon, E. Xu, J. Stromer, C.W. Sensen, "Genomic Data Representation through Images: The MAGPIE/ Bluejay System". In C.W. Sensen [ed.] *Handbook of Genome Research.* Wiley- VCH, Weinheim, 2005 (in press).

C.W. Sensen, "The Future of Large-Scale Life Science Research". In C.W. Sensen [ed.] *Handbook of Genome Research.* Wiley- VCH, Weinheim, 2005 (in press).

P. Gordon, C.W. Sensen, "Oligonucleotide Design from Principle to Practice". In A. Markoff [ed.] *Analytical Tools for DNA, Genes and Genomes. DNA Press*, Eagleville, PA (in press).

BOOKS EDITED:

C.W. Sensen [Ed.], *Handbook of Genome Research.* Wiley-VCH, Weinheim, 2005. 618 pages.

INVITED TALKS:

University of Arkansas at Little Rock (2004): C.W. Sensen: *From 2D to 4D Bioinformatics.*

Germany-Canada / Agricultural-Genomics Team-building at the Rafter Six Ranch in Kananaskis (2004): C.W. Sensen: Bioinformatics in the Age of Systems Biology.

Integrative Bioinformatics - Aspects of the Virtual Cell. Schloss Dagstuhl, Germany (2004): C.W. Sensen: *From 2D to 4D Bioinformatics.*

Bioinformatics Colloqium at the Ludwig Maximilians Universität in Munich, Germany (2004): C.W. Sensen: From 2D to 4D Bioinformatics.

7th International ISSX Meeting in Vancouver (2004): C.W. Sensen: *Bioinformatics and Visual Genomics: Seeing Genes, Proteins and Metabolism.*

Fourth Virtual Conference on Genomics and Bioinformatics (2004): C.W. Sensen: Bluejay: *A Biological Sequence Browser featuring Knowledge Integration.*

Plant Biotechnology Institute in Saskatoon (2004): C.W. Sensen: From 2D to 4D Bioinformatics.

National Genomics and Proteomics Symposium in Vancouver (2004) C.W. Sensen: *An Integrated and Distributed Bioinformatics Platform for Genome Canada.*

5th Annual Spanish Bioinformatics Conference in Barcelona, Spain (2004) C.W. Sensen: *From 2D to 4D Bioinformatics: Using the Genome Canada Bioinformatics Platform for Science.*

Das Bild in der Wissenschaft, Berlin (2004) C.W. Sensen: *Making Virtual Reality of a Fantastic Voyage.*

BioInnovation Center Dresden (2004) C.W. Sensen: *From 2D to 4D Bioinformatics.*

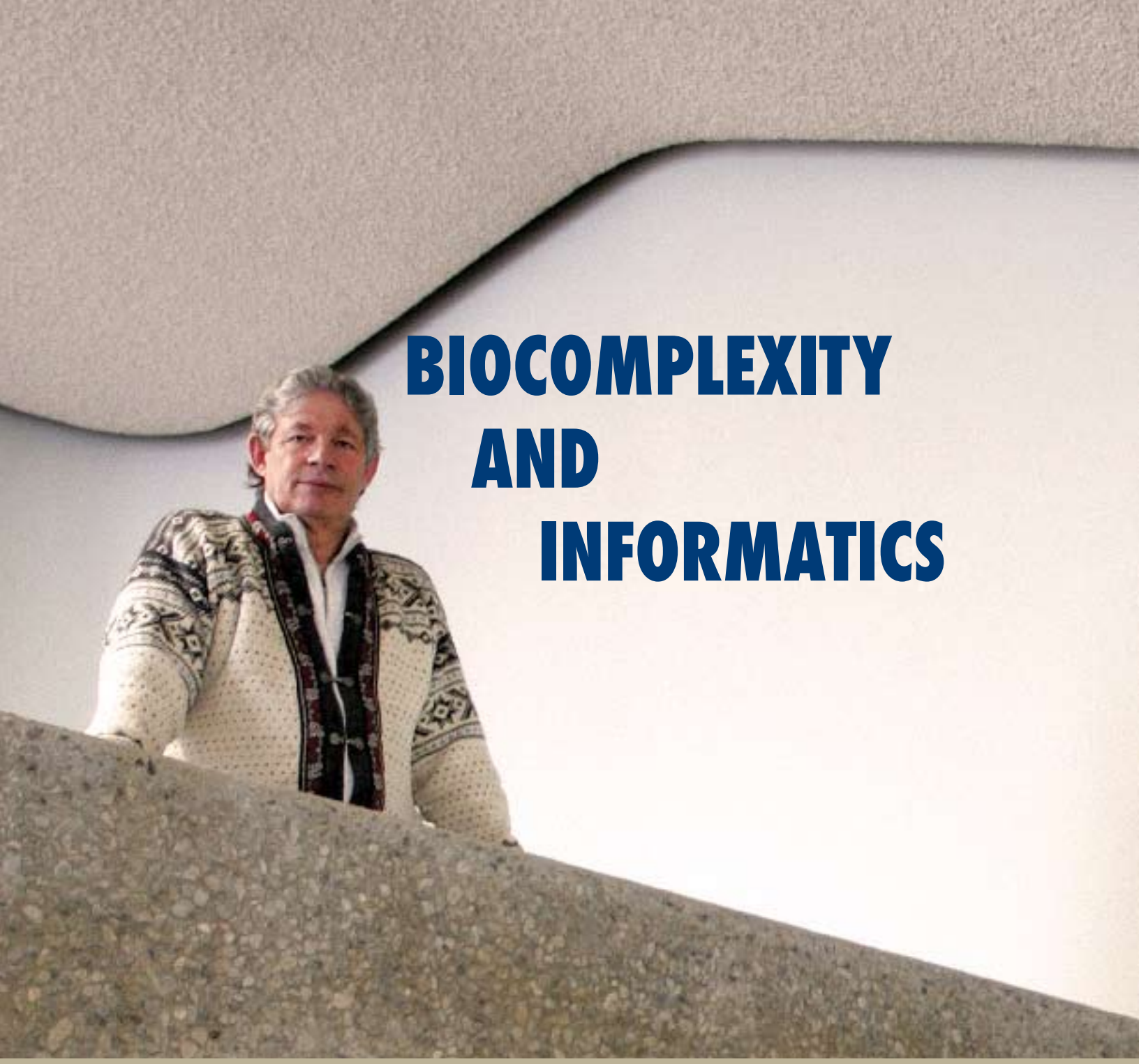
Advanced Digital Technology in Head and Neck Reconstruction in Banff (2005): C.W. Sensen: *4D Bioinformatics and Medical Informatics.*

World Congress on Microarray Technology in Vancouver (2005): C.W. Sensen: *Visual Representation of Gene Expression Patterns using Bluejay.*

2005 Annual GRID event – Western GRID Summit: C.W. Sensen: *GRID and Visualization efforts at the Sun Center of Excellence for Visual Genomics.*

VanBUG talk in Vancouver (2005): C.W. Sensen: *From 2D to 4D Bioinformatics.*

Canadian Genomic Mission to Denmark (2005): C.W. Sensen: *From 2D to 4D Bioinformatics.*



BIOCOMPLEXITY AND INFORMATICS

The Institute for Biocomplexity and Informatics was established for the exploration and understanding of the logic, structure and dynamics of genetic regulatory networks.

STUART KAUFFMAN

iCORE Chair
University of Calgary
http://www.ibi.ucalgary.ca/

EXECUTIVE SUMMARY

The Institute for Biocomplexity and Informatics (IBI) was proposed during the summer of 2004, and approved in the late Fall of 2004. This report therefore covers the first three months of actual operation of the IBI – January, February, and March of 2005.

During these first three months of operation, a full range of normal startup activities were accomplished.

- Deputy Director Bob Este was hired effective January 1rst 2005
- Initial connection and potential collaboration networks were established both on campus at the University of Calgary and elsewhere (other universities, private enterprise; government)
- Director Dr Stuart Kauffman was hired effective February 1rst 2005
- Physical offices were established at the University of Calgary, February 15th 2005
- Postdoctoral fellow Dr André Ribeiro and contract research assistant Chris Davis were retained
- Junior faculty, postdoctoral fellows, and graduate students positions were advertised
- Formal relations was established with the Alberta Innovation Center for Machine Learning (AICML) at the University of Alberta for the purposes of exploratory research collaboration and the hire of a postdoctoral student to work in connection with the IBI
- IBI was established as an official "institute" at the University of Calgary, in accordance with University of Calgary policy
- Strategic plans and meetings with key players (were put in place) to pursue additional funding for the IBI

Strategic plans were begun for other aspects of IBI development and activities including:

- Plans to establish wet lab space for the IBI at the University of Calgary and aquire appropriate laboratory research equipment and the placement of computer networks
- Establishing the setup for the inaugural annual IBI conference at the Banff Centre
- Establishing ongoing collaboration with virtual institute members, and especially, ongoing collaboration among the University of Calgary departments that are an integral part of the IBI (Biological Sciences, Physics and Astronomy, Computer Science, Electrical and Computer Engineering, and Biochemistry and Molecular Biology [Faculty of Medicine])

In addition, extensive initial planning has taken place for expansion of the IBI's interrelated theoretical and experimental research capacities. Theoretical work has moved ahead strongly in the first three months, extending the original research strands of the IBI to now include extensive examination of cancer and stem cell differentiation research, mechanisms, technologies, and outcomes. In addition, focused exploration of screening approaches and techniques to identify small molecules that control stem cell and cancer cell differentiation is underway. Substantial efforts have begun in the preparation of patents stemming from this exploration.

RESEARCH PROGRAM OVERVIEW

The IBI was established for the exploration and understanding of the logic, structure and dynamics of genetic regulatory networks, and identified the following three research strands in the proposed research program to achieve this understanding:

1) The generation of models of small known networks

2) Solving of the "inverse problem" using machine learning

3) Using the ensemble approach to construct model genetic networks

In the first three months of operation, the IBI has commenced early-stage investigative programs in all three of these areas. Logically, with the IBI wet lab still to be built, during the first three months of operation much of this work has been restricted to extensive literature review and theoretical investigation; however, this work has not only been very fruitful in its own right, but is essential for the design and activation of the laboratory experimental program which is now in the early stages of development.

RESEARCH PROJECTS

Based on the original set of research program goals, and with the addition of new work that has been undertaken since the IBI commenced operations to augment these initial goals, work of the IBI during the first three months of operation has yielded the following:

1) Examination of the effects of noise on ergodic sets among attractors in Boolean networks

Randy Goebel, Stuart Kauffman, Bob Este and Brian Unger at the 2005 IBI Launch

2) Development and extension of "Califano" inverse engineering algorithm to time series gene expression data

3) Literature review with respect to cancer, stem cells, transdifferentiation and differentiation therapy in preparation for experimental work

4) Project with AICML has been laid out to extend "Califano" algorithm

This work has created the foundation for:

1) Extension of "Califano" algorithm to realistic molecular simulations of genetic regulatory networks (in collaboration with AICML)

2) Extension of literature review into a patent application regarding a new approach to cancer therapy

3) Clarification of experimental procedures for cell- and molecular-based assays concerning stem cell differentiation and cancer stem cell differentiation

OBJECTIVES FOR NEXT YEAR

The research plan for the next twelve months includes extensive work in the strongly interrelated theoretical, experimental, invention, and fund-raising realms.

With regard to theory, we first expect to explore and develop a suite of theoretical approaches having to do with noise in ergodic sets related to theories of cell types and cell differentiation. This work has already begun and will be extensively developed. We are actively laying the foundation to work closely with AICML at the University of Alberta, especially in the areas of collection, analysis, and synthesis of data collected from novel experiments to be carried out at the University of Calgary wet lab and elsewhere. Initial collaboration in this area has already begun and will be extensively developed as the IBI's own wet lab is operational.

With regard to experiments carried out at the University of Calgary wet lab and in other venues, we expect to carry out novel work on cancer and stem cell differentiation experimental design, techniques and procedures, and data collection. This will include extensive collaborative work having to do with the screening of small molecules that control stem cell and cancer cell differentiation. As a result (and especially in collaboration with the AICML), this wet lab experimentation and collaboration will lead to ongo-

ing exploration and implementation of novel machine learning approaches and strategies.

With regard to invention, we expect that the collaborative theoretical and experimental work now beginning and being extensively planned as briefly described above will follow initial and very promising work that has already been undertaken to do with the generation of new patentable ideas and inventions. All of this indicates that the work of the IBI will be of first rank importance in the general arena of systems biology and biomedicine.

Inventions stemming directly from this first rank theoretical and experimental work of the IBI have very strong potential for commercialization; therefore, aggressive exploration and development of additional funding sources is now being strategized.

RESEARCH TEAM MEMBERS AND CONTRIBUTIONS

NAME	ROLE/TOPIC
Dr Stuart Kauffman	IBI Director
	Associate member of the Southern Alberta Cancer Research Institute awarded the Trotter Prize in March 2005 Co-authored seven publications
Bob Este	IBI Deputy Director
	Presented or had papers accepted for presentation and publication with the 2005 IEEE International Conference on Systems, Man, and Cybernetics ('Intelligent Information Infrastructures for Distributed Systems') in Hawaii, and with UNESCO Heritage of Technology 2005 in Gdansk, Poland.
Dr André Ribeiro	Postdoctoral Fellow
Chris Davis	Contracted Research Assistant

Stuart Kauffman with some IBI research team members and collaborators, Banff 2005

COLLABORATIONS

DR KAUFFMAN HAS CO-AUTHORED AND SUBMITTED FOR PUBLICATION PAPERS WITH:	
Ilya Shmulevich MD	Anderson Cancer Center
Philip Clayton	Claremont School of Theology
Richard Melmon	Founder, NetService Ventures Group
Wim Hordjik	Santa Fe Institute
Sheldon Dealy	University of New Mexico
Josh Socolar	Duke University
John Grefenstette	George Mason University

INTELLECTUAL PROPERTY

In the first three months of operation, the following developments have taken place in the realm of intellectual property: extensive review of the literature having to do with cancer and stem cell differentiation has commenced, extensive discussions have taken place with legal counsel for the University of Calgary and advisory personnel of University Technologies Inc. of the University of Calgary, addressing the polices, processes and procedures that relate to the researching, development, and filing of patents based on the work of the IBI, and original patent documents have been drafted in preparation for filing.

The implications of these developments include the following: the knowledge base of the IBI regarding intellectual property is becoming robust and substantial, the present theoretical work of the IBI is demonstrating a strong capacity for creative problem solving, invention, and new systems biology knowledge generation, and the theoretical knowledge base of the IBI is becoming extremely robust in preparation for the extensive experimental work that will follow shortly.

FUNDING

Stuart Kauffman, as one of our newest iCORE Chairs, is busy ramping up his team and equipping his research lab with funds from his iCORE Chair ($910K) and the University of Calgary (~$372K).

PUBLICATIONS

REFEREED JOURNAL PUBLICATIONS

"Noise in a Small Genetic Circuit" – Ilya Shmulevich, Trent Tolouse, Stuart Kauffman – accepted pending minor revisions, *Complexity*, 2005

"Pathways of Differentiation" – with Josh Socolar, Sheldon Dealy, Stuart Kauffman – accepted pending minor revisions, *Complexity*, 2005

"Analysis of Coevolutionary Landscapes" – Wim Hordjik, Stuart Kauffman – accepted pending minor revisions, Complexity, 2005

"Are Eukaryotic Cells in the Ordered Regime?" -- Max Aldana, Ilya Shmulevich, Stuart Kauffman – submitted, *Proceedings of the National Academy of Science*, USA

"Distributed Robustness in Genetic Nets" – Max Aldana, Stuart Kauffman – submitted, *Proceedings of the National Academy of Science*, USA

"The Rise of Animalia" – Richard Melmon, Stuart Kauffman – submitted, BioEssays, 2005

"Agency, Emergence and Organization" – Philip Clayton, Stuart Kauffman – submitted, *Biology and Philosophy*, 2005

REFEREED CONFERENCE PROCEEDINGS

Este, Robert A., "New Minds for New Times: A Study of Andragogical Instruction for Engineers," *Proc. 4th Int'l Conf. Heritage of Technology*, 2005: 87-94; Gdansk, Poland

Este, Robert A., and Stuart A. Kauffman, "Some Thoughts on Unprecedented Conceptual Challenges Presented by Holonic Multi-Agent Systems," *IEEE International Conference on Systems, Man, and Cybernetics* ('Intelligent Information Infrastructures for Distributed Systems'); accepted for conference presentation, October 2005

SPECIAL / INVITED PRESENTATIONS

Kauffman, Stuart A., "Toward a Physical Definition of Life", *Endowed Lecture Series, at the ceremony awarding the Trotter Prize, College of Science* (in collaboration with The Dwight Look College of Engineering), Texas A&M University, March 2005

AWARDS

Kauffman, Stuart A., The Trotter Prize, College of Science (in collaboration with The Dwight Look College of Engineering), Texas A&M University, March 2005

ABOUT iCORE

The role of the Alberta Informatics Circle of Research Excellence

iCORE was established in October 1999 by the Government of Alberta to foster world-class university-based research that supports the ICT sector. This investment stems from a belief that strong fundamental research is at the core of a healthy economic sector, which in turn creates social, cultural and economic advantages for Albertans.

Mission

The mission of the Alberta Informatics Circle of Research Excellence (iCORE) is to attract and grow a critical mass of exceptional researchers in the field of informatics, that is, areas of computer science, electrical and computer engineering, physics, mathematics and other disciplines related to information and communications technology (ICT).

Target areas

iCORE is directing its support to areas in which Alberta has a chance to develop internationally recognized research teams. It is also focusing on areas in which Alberta companies are active, so that intellectual property and valuable knowledge workers resulting from iCORE's investment will have compelling reasons to stay in Alberta.

Randy Goebel and Brian Unger at the 2005 Banff Summit

Focus on people

iCORE invests in people – the highest caliber research scientists who work on fundamental and applied problems in informatics. Around these leaders, world-class research teams are developed.

FLAGSHIP GRANT PROGRAMS

Chair and Professor Establishment (CPE) Grants

iCORE Chairs are awarded to exceptional researchers with outstanding research records that place them in the top five percent of their fields. iCORE Professors are mid-career researchers with outstanding potential whose record may not yet justify a Chair position.

Funding research teams may vary in size from a single Chair or Professor working alone to teams with ten or more members. iCORE funds can be used to cover the salaries of chairs, professors, research associates, postdoctoral fellows and graduate students, as well as some research operating and equipment costs. The research itself may range from fundamental to applied.

CPE grants are normally awarded for five years, represent one-half or less of the total budget, and are renewable on a competitive basis.

Industry Chair Establishment (ICE) Grants

iCORE Industrial Chairs are awarded to researchers undertaking high-caliber, internationally competitive research. Industrial Chairs are always developed in conjunction with a sponsor company(s) that has demonstrated a willingness and ability to collaborate closely with the research team, and to exploit proposed research in Alberta. The program is also typically matched with NSERC awards.

Funded research teams may vary in size from one to ten or more members, and may include a Chair, professors, research associates, postdoctoral researchers, graduate students and research staff. The funds may also cover operating and equipment costs.

ICE grants are normally awarded for five years, represent one-third or less of the total budget, and are renewable on a competitive basis.

EMERGING CLUSTERS

NETWORKS AND WIRELESS COMMUNICATION		START DATE
Wireless Communications	Dr Norman C. Beaulieu	2000-01
Advanced Technology Information Processing Systems	Dr Graham Jullien	2000-01
Wireless Location	Dr Gérard Lachapelle	2000-01
Broadband Wireless Networks, Protocols, Applications, and Performance	Dr Carey Williamson	2000-01
Wireless Traffic Modelling and Simulation	Dr Carey Williamson	2001-02
High Capacity Digital Communications	Dr Christian Schlegel	2001-02
Algorithmic Number Theory and Cryptography	Dr Hugh Williams	2001-02
Wireless Science and Technology	Dr Jim Haslett	2002-03
Intelligent RF Radio Technology	Dr Fadhel Ghannouchi	2005-06
NANOSCALE AND QUANTUM INFORMATICS		
Nanoscale Engineering Physics Initiative	Dr Michael Brett/Dr Mark Freeman	2000-01
Thin Film Engineering	Dr Michael Brett	2003-04
Nanoscale ICT	Dr Robert Wolkow	2002-03
Quantum Information Science	Dr Barry Sanders	2003-04
INTELLIGENT SOFTWARE SYSTEMS		
High Performance Artificial Intelligence	Dr Jonathan Schaeffer	2000-01
Software Engineering Decision Support	Dr Guenther Ruhe	2001-02
Reinforcement Learning and Artificial Intelligence	Dr Rich Sutton	2003-04
Intelligent Sensing Systems	Dr Hong Zhang	2003-04
Collaborative Virtual Environments	Dr Pierre Boulanger	2005-06
Applied Bioinformatics	Dr Christoph Sensen	2005-06
Biocomplexity and Informatics	Dr Stuart Kauffman	2005-06

SUPPORT PROGRAMS

Graduate Student Scholarships (GSS)
- Designed to recruit exceptional graduate students
- Operates in conjunction with NSERC, Alberta Ingenuity and other major awards
- Up to two hundred awards annually

Visiting Professor (VP) Grants
- Designed to bring internationally recognized researchers to Alberta for six months to two years to develop partnerships and possibly recruit Chairs or Professors

ICT Strategy Planning and Recruiting (ISPR) Grants
- Designed to support the interaction with potential candidates for major iCORE award programs
- Supports ICT conferences and workshops in Alberta in areas where a Chair or Professor award may be made

Banff Informatics Summit
- An annual event that brings together iCORE researchers and their national and international colleagues

For more information on iCORE's strategy and areas of research focus, visit www.icore.ca