2018
A YEAR IN REVIEW

ANNUM

THE EDWARD S. ROGERS SR. DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

The Edward S. Rogers Sr. Department of Electrical & Computer Engineering
UNIVERSITY OF TORONTO

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Above and beyond

PHOTO BY RAINA+WILSON

Tune in to the evening news on any given day and it won't take long before you hear about some of the exciting innovations in the field of electrical and computer engineering. Artificial intelligence (AI), electric vehicles and quantum computing are just a few areas where electrical and computer engineers are driving some of the innovations behind the technologies that have captured the public's interest.

For electrical and computer engineers, it's often what is "under the hood" of these technologies that is most fascinating. It's the deep convolutional neural networks in the AI area, the power electronics in the electric vehicle's drivetrain or the mystery of quantum entanglement that interest us.

While these technologies are interesting in-and-of-themselves — it is really exciting to take a step back and see the impact these technologies are having on greater society.

The cover story of this issue, Quantum out of the Cold, on page 24, highlights a longstanding partnership between The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE) and Fujitsu Laboratories. This collaboration has resulted in the development of a technology that researchers say rivals the performance of a quantum computer, using regular digital circuits. While the technology is fascinating, so too are its applications — in areas ranging from smart cities to health care. Read on to see how researchers in ECE are working to apply this nascent technology to all sorts of pressing societal challenges.

Advances in digital technologies have helped to create, store and share reams of data about individuals, generated from the smartphone in their pockets. But who is accessing this data and why? Read how Professor David Lie's interdisciplinary research with Professor Lisa Austin of the Faculty of Law is helping to improve digital transparency between corporations, government and users. Flip to page 8 to read how they are tackling privacy issues where technology and law meet.

These are just a few examples of the myriad of ways in which ECE researchers, students and alumni are making an impact on society. This magazine highlights some of these stories from the past year — and the people behind them. I welcome your feedback and invite you to connect with us; you may reach me directly at chair@ece.utoronto.ca.

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ANNUM 2018

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SECTIONS

UNDERGRADUATE

U of T Engineering Launches Artificial Intelligence Minor and Certificate

Preparing the leaders of tomorrow for what some are calling the fourth industrial revolution, students will be poised to apply AI in diverse fields

> Security is about either allowing or denying access to data, but privacy is about granting access to data under certain conditions and making sure those conditions are enforced. This requires transparency into what is being done with the data.

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Graduate Students Awarded Vanier Scholarships

From designing microfluidic devices to entangled photon lasers, graduate students are recognized for their excellence both inside and out of the lab

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ECE Professor Leads UTLedger-Hub for Crypto-economic Block-chain Technology

Multidisciplinary project aims to unite researchers to apply blockchain technology in fields ranging from law to finance

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Three ECE Professors Named Vector Institute Faculty Affiliates

The Vector Institute for Artificial Intelligence brings together leading researchers in deep learning, machine learning and artificial intelligence

ALUMNI

ECE Donors Follow Their Hearts

Benefactors give back to where it all started, with an eye on the future

OUR STORY

Founded in 1909, The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE) maintains a proud history of world-leading research and innovative education. We are the top-ranked ECE department in Canada and home to 99 professors, 658 graduate students and 1,540 undergraduates. Our classrooms, halls and laboratories hum with energy and creativity.

ECE students and professors work together to solve some of the most pressing issues of our time — we are recognized leaders in the fields of smart grid technology, mobile application development, next-generation networks, and emerging areas such as biomedical engineering, robotics and machine learning.

Our graduates go on to prominent careers in engineering, finance, medicine, law and more — their options are truly unlimited.

Among our faculty are 31 Fellows of the IEEE, 10 Fellows of the Royal Society of Canada, 15 Fellows of the Canadian Academy of Engineering, and four E.W.R. Steacie Fellows, a prize awarded to the brightest and most promising scientists and engineers across the country. ECE is a hotbed of research commercialization, with more than 155 inventions disclosed and 106 patents filed over the past five years — by far the most productive department for new inventions at the University of Toronto. Read on to find out what makes us the top-ranked ECE department in Canada.

QS World University Rankings 2018

#1 *in* Canada

Electrical & Electronic Engineering

#10 *in* North America

Electrical & Electronic Engineering

#24 *in* the World

Electrical & Electronic Engineering

#1 *in* Canada

Computer Science & Information Systems

#7 *in* North America

Computer Science & Information Systems

#10 *in* the World

Computer Science & Information Systems

1,540 Undergraduate students

658 Graduate students

99 Professors, including Emeritus

76 Post-docs

53 Admin & tech staff

17 Research associates

9 Visiting professors

23

Chair titles held by ECE faculty in 2017–2018, including Canada Research Chairs, Endowed Research Chairs, Industrial Research Chairs and U *of* T Distinguished Professor Chairs

$53,132

Average salary earned by ECE students on PEY Co-op placements in 2018-2019

155
INVENTIONS OUT OF ECE SINCE 2013

106
PATENT APPLICATIONS OUT OF ECE SINCE 2013

Times Higher Education World University Rankings 2018–2019

Engineering & Technology Universities

#1
IN CANADA

#15
IN NORTH AMERICA

#29
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MIND THE TRANSPARENCY GAP

BY JESSICA MACINNIS

App users are providing personal information to businesses and organizations at an increasing rate, but it's unclear to users exactly what information they are providing — and why. Professor David Lie from The Edward S. Rogers Sr. Department of Electrical & Computer Engineering is working with Professor Lisa Austin from the Faculty of Law to tackle privacy issues where technology and law meet

A lawyer, a computer engineer and an economist open an app and read a privacy policy. There's no joke here, but if there were, there would be three different punchlines.

Computer engineers have long been involved in developing the technologies that protect computer and internet users, governments and companies from digital attacks. From Trusted Computing to hardware and software security co-design, detecting and preventing malicious activities has long been in the domain of engineers. But what role do they play in internet privacy?

Professor David Lie is embarking on a series of multidisciplinary projects to answer that question. "I've been working in the area of security for a long time — security is about making sure bad people don't get at your data, and do bad things to you," says Lie. "Privacy is much more nuanced: security is about either allowing or denying access to data, but privacy is about granting access to data under certain conditions and making sure those conditions are enforced. This requires transparency into what is being done with the data." And it is going to take both legal and technology experts to figure out what that transparency looks like.

Lie is collaborating with Professors Lisa Austin of the Faculty of Law and Avi Goldfarb of the Rotman School of Management to tackle some of the ongoing and emerging issues around digital privacy. They've joined together to create the Information Technology, Transparency, and Transformation (IT3) Lab with the objective of making the implications and effects of data collection transparent to users, companies and regulatory bodies.

With initial funding for one of their projects from the Office of the Privacy Commissioner of Canada (OPC), the IT3 Lab was established to approach issues of privacy in technology through the lenses of both law and software. "For a long time, there have been a lot of silos between law

and technology and I think we are well beyond the point where lawyers and policy makers just need a 'techie' friend to answer technical questions as laws are written and interpreted," says Austin. "Increasingly, the kinds of questions that I am interested in — even when they are more philosophically informed, or about legal frameworks — can't be answered without really working with people in computer engineering and computer science." IT3's approach is to ask what transparency means in the 21st century and to create new ways to ensure digital transparency in an increasingly digital society.

In 2017, IT3 received the University of Toronto's Connaught Global Challenge Award, bestowed to collaborations involving leading U of T researchers and students from multiple disciplines. Soon after, the Lab embarked on their first project: developing transparency-enhancing technology. "In law, we have all these human-centric ways of doing things," says Austin. "You have actual people looking at actual things: it's slow and when it comes to looking at privacy in things like apps, it's a bit short-sighted to apply these human-centric tools to technology." Instead of using traditional methods of identifying privacy concerns in technology — having a legal team read a privacy policy and look at the front end of an app — the team sought to use technology to help regulators identify transparency issues within these technologies. "It's kind of like fighting fire with fire," says Lie. "Why not utilize these very technologies to explore these legal issues in the technology?"

As it stands, regulators like the OPC will read a privacy policy and assess whether the user interface complies with the stated policy. "Right now, the role of a regulator is to make sure that an app's privacy policy conforms to the laws that govern data privacy," says Lie. "But what is more challenging for regulators is that they also need to make sure that an app complies to its own declared privacy policy." Regulators are experts in interpreting and applying legislation — but it's unlikely that they would be able to easily identify or analyze what is 'under the hood' of an app, they simply lack the tools to enforce this part of their mandate. To overcome this, Lie and the team at IT3 used machine learning to create AppTrans, a working prototype to help regulators do just that.

The team utilized a crowdsourcing site to hire people to interpret single sentences from various applications' privacy policies and label which privacy policies stated they were collecting specific data. They then took the labelled data to Austin and her students to verify that they were accurately identified before feeding the labelled data through a machine learning algorithm. The IT3 team found that the general public was as accurate as lawyers were in interpreting single sentences of a given privacy policy, but faced challenges when they sought to train the datasets. "The problem with a machine learning algorithm is that humans have all sorts of ways of saying something with the same or similar meaning in a privacy policy," says Lie. "You can say 'location' or you can say 'GPS' and we needed to train the system not to confuse things like 'we are collecting your list of contacts' with 'we will contact you.'"

Once the accuracy of the labelled data was established the team did data flow analysis — application analysis that looked at the code and tracked what data was actually being collected. "Then we mapped the two: the automated analysis of the privacy policy and the software's code," says

> Security is about either allowing or denying access to data, but privacy is about granting access to data under certain conditions and making sure those conditions are enforced. This requires transparency into what is being done with the data.

Austin. "So, if the code shows that the application is getting your device's location information and sending it off device, but it doesn't explicitly say it was doing so in the privacy policy, the app would be flagged."

> The IT3 team found that the majority of the nearly 800 apps they analyzed were not complying with their own privacy policies. "More than 60 per cent of the apps we looked at violated their own stated privacy policy," says Lie. "And not because these developers were intentionally acting maliciously." In more than 80 per cent of the cases where the app was not in compliance with its own privacy policy, the infringement was caused when the app's developers used a third-party advertising or analytics library. "For example, a calculator app's privacy policy could state that it's not collecting any information from your device — which is what a user would expect, ultimately, it's just a calculator," says Austin. "But because the developers had installed a third-party advertising library to monetize the app, the advertising library is collecting various information to target ads to the users."

For Lie, this is just one example of where laws and technology are intersecting but legal and technology communities are not communicating with each other. "I think it's similar to how users don't read the privacy policies of the apps they install," says Lie. "Well, developers don't read privacy policies of the third-party libraries they use either — but legally, it is the app developers' responsibility to understand and declare that." This transparency gap is the crux of the issue for Austin and Lie — developers don't have the privacy knowledge to understand their responsibilities, and the legal and regulatory communities don't have the technical capacity to be able to identify when privacy laws and policies are being violated.

Their hope is that tools like AppTrans will assist both regulators and developers — as well as individual users. By automating the classification of legal information, they hope to build more interactive tools that would help users understand the privacy policies that they are agreeing to. This would help both individuals and regulators understand what is going on in their phones and more broadly in a sector. "Part of the consent problem is that it's not just that people don't read privacy policies — but how do you understand what it means to your privacy to say yes or no to a particular practice at a particular moment in time," says Austin. "It's the aggregate practices across time that create privacy vulnerabilities — so some of our long-term interests are looking at how we can help people understand this."

The IT3 team has embarked on a number of other projects that delve into the intersection of law and technology. "A really interesting area that we are looking at next is smart cities," says Lie. "By definition, smart cities use data to enable municipal leaders to make better decisions about the services we use every day, from traffic lights to waste collection." Smart city proponents propose that this data should not be considered the proprietary asset of a few companies but open and accessible to others seeking to innovate, but truly open data brings a whole host of privacy concerns and trade-offs. Austin and Lie are looking at the privacy risks with open data and how to mitigate those risks with both technology and legislation.

"For a long time, we'd have people developing technologies and then handing them over to lawyers to look at the end product," says Lie. "But technology has advanced to a point where we need to work together, both in developing and understanding the laws and regulations that govern our digital privacy and also by utilizing these advances in technology to help interpret and practice law — it makes sense for both sides that we work more closely together." A

NOTHING VENTURED, NOTHING GAINED

It's been a decade since Natasha Baker, Michael Montano and Nelson Wu were undergraduate students in The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE). In the years following their graduation, they each took a separate entrepreneurial path, but all three were drawn by the gravitational pull of Silicon Valley

BY JESSICA MACINNIS
PHOTOGRAPHY BY MICHELLE YEE

In 2008, with the global financial crisis in full swing, graduates were facing an uncertain future. Despite the economic downturn, or perhaps because of it, three ECE alumni embarked on an entrepreneurial path soon after graduating by leveraging their technical knowledge honed as undergraduates to help bring their ideas to market.

During her third year of studies as an electrical engineering student, Natasha Baker took a part-time job at National Instruments that snowballed into a full-time technical role on their simulation and modelling team after graduation.

Baker was building a circuit board for an upcoming tradeshow in hopes of showing off the circuit board design software the company had created. Her biggest challenge was that her time was consumed by trying to find all of the different component models she needed to build the board. "I remember thinking, someone should solve this problem — how can engineers innovate if they are constantly reinventing the wheel on the most basic, fundamental building blocks that you need to design a product?" says Baker. "And then I remember thinking, well, maybe I could solve it."

After months of juggling full-time work and growing the skillset she knew she needed to launch a startup, Baker quit her job and began to focus on building her company. "I just really believed in this idea: I didn't have a team, I didn't really have the business skills and I didn't have any funds," says Baker. "But as a student, I had heard so many stories from entrepreneurs who were really candid about the risks but really inspired me to make the leap anyway — and that's how SnapEDA started."

Baker describes SnapEDA's mission as helping hardware designers to bring their products to life cheaper and faster. They do this by providing a search engine for building circuit boards: "A hardware designer could be building everything from an electric airplane to satellites, and we provide the blueprints that they would need to build those devices a lot faster," says Baker. "Rather than spending their time creating those blueprints from scratch, they can just drag and drop them into their design — that's where our focus is today."

SnapEDA's business model is not based on user subscription fees, in fact that's part of the company's value proposition. "We provide this search engine for free: it's entirely free for users," says Baker. "But the way we make money is by working with the component manufacturer to help them get those crucial design wins they are looking for." To do this, the company has created a proprietary recommendation engine that looks at the specifications and type of components that a user is looking for and matches them with the best fit for their needs. The companies pay SnapEDA for each click their product receives after being recommended.

"There are about 300 million electronic components out there — finding the best one is always really challenging and I know that because I was once on the other end of this problem," says Baker. "Today, we have 18 people on our team who are really passionate about helping our 150,000 registered users make better design decisions." In 2018, SnapEDA's revenue grew five times what it was in the previous year. "It's interesting, we are constantly getting approached by

companies about acquisitions — which is new for us," says Baker. "But it's not because the vision has changed or that the business model has changed, it's just that now we have traction."

Baker is looking to increase the number of tools SnapEDA supports and expand the types of content they provide. "Right now, we only support board-level models but we're looking at supporting other types of models and how we can enable larger building blocks that users can download — like larger reference design templates," says Baker. "But overall I'd say our original goal and our ongoing plan is to make great tools for engineers."

Michael Montano had been building and selling websites since high school and followed his love of math and physics to the University of Toronto to study electrical and computer engineering. By third year, his interest in the world of startups had been piqued — he began reading everything he could on the startup ecosystem: "Even in undergrad I was still building and selling websites," says Montano. "By third year, I knew that I wanted to do a startup."

In the second semester of his final year in ECE, Montano and classmate Christopher Golda applied and were accepted to Y Combinator, a seed accelerator that counts noteworthy startups like Airbnb, Dropbox and Reddit as alumni of their program. "We pitched a brand-new idea, something that we were really passionate about," says Montano. "We wanted to build something that would help people follow conversations online."

Through this, the idea for their company, BackType, emerged: "We had this hypothesis that the internet would become much less static and informational and in fact, would become much more dynamic and conversational," says Montano. "So, we wanted to help people tap into that and get value out of it." Together, they built a service that would help people to follow conversations online by finding news and curating what people were talking about in real time. As his final exams were wrapping up, Montano headed to Boston to complete the Y Combinator program, later moving to Silicon Valley to grow their company.

By the time BackType was acquired by Twitter they had grown to six team members and Montano began working on delivering publisher analytics products to some of Twitter's publishing partners, like the Huffington Post and the New York Times. "At the same time, we continued to contribute to a piece of software we had developed at BackType called Storm, which is now an Apache product," says Montano. "We made it open-source after we joined Twitter and continued to develop it after our acquisition and integrated it into the Twitter stack."

Later Montano led the advertising and analytics team at Twitter as Director of Engineering before moving to the consumer side of the company in 2016 where he led everything from

We had this hypothesis that the internet would become much less static and informational and in fact, would become much more dynamic and conversational, so, we wanted to help people tap into that and get value out of it.

MICHAEL MONTANO

starting the home timeline to all of computer engineering. In 2018, Montano was named the head of engineering at Twitter, leading the full team of about 1,500 engineers and developers. "I get to work with incredibly talented people who are working on really exciting things: from our consumer product, to our ads, to our security and video engineering teams," says Montano. "I miss writing code but I've always loved building teams, which is really the job of a founder, and I get to do that in this role at Twitter."

As for what's kept him at Twitter for nearly a decade? "It's really the product — I think Twitter is so meaningful and impactful in the world and it really aligned with the same kind of vision we had for our startup," says Montano. "We took a different approach with BackType, but I think the overall goals are really closely aligned so it's been a great fit for me professionally, but also personally."

Nelson Wu knows the power of a community: in fact, he's built a company around it.

Wu, with co-founder Steve El-Hage, founded Massdrop in 2012, a digital commerce platform that's driven by communities of enthusiasts. From mechanical keyboards to photography or even knitting, Massdrop brings people with common passions together and helps them leverage their communities into buying power.

"Massdrop has about six million users, who belong to one of about 20 communities," says Wu. "Through discussions and polls members interact with each other to discuss products of interest to their specific communities — everything from camera lenses to high-end fountain pens." Massdrop uses that information to negotiate group purchases and product modifications for requested items with manufacturers.

Massdrop has grown to more than 150 employees and has secured $100 million in funding, and while the company's growth was fast, it was not easy. Wu and El-Hage met in Toronto and with the seed of the idea for Massdrop planted, the two worked quickly to get the company launched and moved to Silicon Valley as soon as they had the last line of code written for their initial site.

Working out of a hacker hostel — houses filled with aspiring entrepreneurs who live in close quarters with each other in hopes of building the next great company while combating Silicon Valley's notoriously high rent prices — the two were committed to not just making a better group-buy site, but also creating deep communities.

"Our first product drop was for a luxury car grille; we were able to locate the manufacturer who produced the grilles overseas and we negotiated the price down to less than half of the retail price," says Wu. "We had 200 car enthusiasts buy in at $200 per person and we painstakingly collected payments through PayPal from each group member." With that, the company had quickly made its first $40,000 — but PayPal froze their account when they attempted to transfer the funds to the manufacturer. "In retrospect, I can see how that might look suspicious," says Wu. "But at the time we had so much riding on fulfilling this order that we paid out of pocket and maxed out our credit cards to make it happen."

PayPal released the funds a few weeks later, and soon Massdrop received seed funding from some of the largest venture capital firms in Silicon Valley: Kleiner Perkins, Cowboy Ventures and First Round Capital. Massdrop outgrew the hacker hostel, then their first office space and recently moved to their sixth and largest location. Wu's happy to see Massdrop grow and is also pursuing growth for himself — he's keen to give back to both his alma mater and to aspiring entrepreneurs. "It wasn't that long ago that I was a student with a passion for starting a company but had no idea or direction for where to start," says Wu. "If I can help a young person with a great idea and a lot of passion I'd love the opportunity to — but I don't want to tell them what to do, I want to talk them through decisions and hopefully offer advice about the decision-making process."

If anyone knows, it's Wu: a community can be a powerful thing. A

SUCH GREAT HEIGHTS

BY JESSICA MACINNIS
PHOTOGRAPHY BY RAINA+WILSON

When exploring options for graduate school, Trevor Stirling was looking for a top-notch research program in quantum photonics but he also needed to be close to one of the best trampoline clubs in the country. He found both in Toronto at The Edward S. Rogers Sr. Department of Electrical & Computer Engineering

Forwards, backwards, twisting and turning — from entangling photons to soaring on trampolines graduate student Trevor Stirling is a bit of a thrill seeker. As a member of Canada's national trampoline team, Stirling travels all over the world as a competitive trampoline athlete. And when he's not training six evenings a week? You can find him working on some of the most promising applications for future quantum computing.

A trampoline routine consists of a combination of elements that are judged based on the overall execution of the routine, the difficulty of the skills, and the time the athlete spends in the air: all while performing triple flips 20 feet in the air. Trampoline athletes must start and finish their routine on their feet and perform highly controlled maneuvers while experiencing up to 18g of force between landings. That g-force is nothing compared to the rigors of international competition — and Stirling would not have it any other way.

Stirling first set foot on a trampoline just a little more than a decade ago; his interest was piqued when his sister took up the sport in their hometown of Kelowna, British Columbia. He began lessons and soon started competing: by 2010 he was representing Team Canada internationally.

In 2016, Stirling was an electrical engineering undergraduate student at the University of British Columbia and was juggling his academic responsibilities with his hectic athletic schedule. He had made the Canadian Senior Team and was named the alternate athlete for the 2016 Olympic Games in Brazil. Soon after he was named to the team he tore his ACL, a setback he took in stride. "I still was able to go down to Rio and watch my teammate win gold in the women's event," says Stirling. "Even though I knew that I wouldn't be able to sub in if required, it was an incredible experience to watch my teammates compete on that stage."

Back in Canada, Stirling was starting to think about graduate school. "As an undergraduate student, I worked with Professor Jonathan Holzman who was working on ultrafast photonics out in Kelowna," says Stirling. "Working with him over a few summers and being exposed to research in both classical and quantum photonics was really exciting — I knew it was something I wanted to pursue but I also knew I wanted to continue with trampoline."

With those two seemingly separate goals in mind, he decided to move east to Toronto. "I wanted to stay in Canada so that I could be close to some of the best coaches and facilities in the world, but I also wanted to study integrated quantum photonics," says Stirling. "Toronto offered both."

Stirling joined Professor Amr Helmy's research group in The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE) as an MASc student and later fast-tracked into the PhD program. "My research is in the design of lasers that emit entangled photon pairs," says Stirling. "So, instead of lasers emitting a single photon at a time, they emit two photons simultaneously and the properties of those two photons are linked across space and time." If competing on the international scene seems exhilarating, so too are the potential applications for research like Stirling's.

One of the obstacles in quantum computing is linking quantum bits together. "You can make a chip with many qubits on it, but only a few can communicate with each other at a time," says Stirling. "If we could link all of these bits together the computational power would overtake classical computing very quickly.

These entangled photon pairs will connect different qubits together to link up entire chips." The design and implementation of entangled photon lasers on silicon-based computer chips will be used to interconnect quantum bits on chip to help realize scalable quantum computing. This research could also provide a platform for further research into the applications of quantum light.

Stirling's days are spent in the lab and his evenings spent in the gym; on average, he will train from 9 p.m. until midnight six days a week. Despite the time spent somersaulting through the air, he's still managed to balance his rigorous training and travelling schedule with his research. In 2018, Stirling was awarded a prestigious Vanier Scholarship, an award that acknowledges the potential impact of a graduate student's research while celebrating the student's leadership contributions both on and off campus. "The research topic is what drew me here to ECE. I didn't meet Professor Helmy until after I had enrolled," says Stirling. "But he's turned out to be a fantastic supervisor and I think receiving the Vanier Scholarship is a testament to that."

If you ask Stirling what his long-term goals are, he'd probably ask you to clarify whether you mean for his athletic pursuits or after he completes his graduate studies. And his answers to both would be equally ambitious: "I want to keep competing at the highest possible level for trampoline — I think the Olympics are on the mind of all my teammates but there are so many variables leading up to the games," says Stirling. "But trampoline is one of the few gymnastic sports where athletes continue to improve beyond their teenage years and well into their late twenties or even thirties, so I think I have a bit of time ahead of me."

But if the 2020 Olympic Games are not in the cards for Stirling, there's still a lot to be excited about. "As of right now, I'd love to eventually do research and development for a company that's pushing the bounds of computing into the all optical and/or quantum realm," says Stirling. "This likely means working for a large company, but there are also several smaller startups working in quantum computing and photonic computing, so the options are wide open."

> I wanted to stay in Canada so that I could be close to some of the best coaches and facilities in the world, but I also wanted to study integrated quantum photonics. Toronto offered both.

Whether his path veers towards the Olympics or to photonics, Stirling is confident about what will bounce his way next — trampolinists always land on their feet. A

WATCH THIS SPACE

BY JESSICA MACINNIS
PHOTOGRAPHY BY RAINA + WILSON

Led by an ECE undergraduate student, the University of Toronto Aerospace Team is looking to push the limits of innovation and launch the next generation of students into the field of aerospace along the way

“I had no idea that I could be working on satellites as an undergraduate student,” says Ridwan Howlader. “I just didn’t think it was a possibility.”

Doing what doesn’t seem possible is a bit of a pattern for Howlader as he leads the University of Toronto Aerospace Team (UTAT) — whether it’s breaking records or influencing public policy he’s got his sights set well beyond the horizon.

Howlader’s involvement with UTAT started well before he was a University of Toronto student. “The team came to my high school and encouraged us to enter their competition to design a payload for their rocket,” says Howlader. “They ended up choosing our project which was really exciting at the time.”

Later, as a first-year student Howlader was exploring the University’s Clubs Fair. “I was basically just going from one design club to another to see which one interested me most,” says Howlader. “As I got involved I realized that UTAT gave younger members a lot of opportunity to contribute so I thought it was a good opportunity to learn a lot in a short amount of time.”

As a student in The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE), UTAT was a good fit for Howlader. “A lot of what we do at UTAT involves the things we are learning here in ECE,” says Howlader. “We use power systems, image recognition, data transfer and computer vision — the rocket team relies heavily on the communications side — we use solar panels, sensors, radio signals and transceivers.”

Beginning in roles that involved the design of recovery and avionics systems, Howlader soon found himself as the team’s director of outreach. “I personally benefitted from UTAT’s outreach to high schools so I really wanted to give back in this way,” says Howlader. “It’s really been a focus of UTAT to get younger students excited about aerospace and show them the kinds of things they can get involved with.” In this role, he helped the team expand their reach beyond high schools and to the general public.

His leadership on that front caught the eye of the senior leadership on the team who were looking to make a succession plan so that the team would be well prepared for the next cycle of competitions and outreach activities. “They were looking for someone to lead the team and push student innovation technologically, but also in public engagement,” says Howlader. “As Executive Director, I’m responsible for leading the strategic planning, public relations as well as providing technical oversight for our six divisions and 140 team members.”

UTAT’s six divisions cover both technical and non-technical aspects relating to aerospace and involve undergraduate and graduate students from across a number of disciplines who work together to advance the team’s goals.

The Unmanned Aerial Vehicles (UAV) division makes fixed wing drones: the kind that take off and land like an airplane. In this division, team members look to build and improve small unmanned aircraft with more advanced autopilots and payload capabilities. “The UAV team is working towards a big competition in 2019 that will take place in Alma, Quebec,” says Howlader. “They’ll be assigned a real-world problem from a variety of sectors and will have to fly our UAV, locate components, collect data and deliver a design presentation.”

Where the UAV team is focused on optimizing and improving aircrafts, the Aerial Robotics Division is looking to design and build innovative quadcopter drones — the kind that take off and move sideways. “The Aerial Robotics team utilizes a lot of what we learn in electrical and computer engineering,” says Howlader. “Computer vision, control algorithms and systems engineering all play a big part in what our aerial robotics team is working on.”

The Space Systems team builds satellites and are working on the

We are building what’s called a hybrid rocket, one that involves an engine with both a solid core and a liquid oxidizer.

development of their microbiology nanosatellite called the HERON Mk II. "They're building what's called a 3U satellite — a 1U nanosatellite is about a 10 centimetre cube — so our team is building one three times that, about the size of a loaf of bread," says Howlader. "In there is a biology experiment, a lot of electronics that are going to help us communicate between the experiment and earth, and the team is incorporating solar panels and an antenna."

UTAT's Rocketry division is focused on breaking the Canadian amateur altitude record in 2019. "We are building what's called a hybrid rocket, one that involves an engine with both a solid core and a liquid oxidizer," says Howlader. "The idea is that we will take our functioning rocket that we've been testing and put it on our new engine and launch that to break the altitude record for an amateur team — we're hoping to see it break 13.4 kilometres to get that record."

Looking beyond 2019 and further than 13.4 kilometres, the Rocketry team is also posed to participate in the Base 11 Space Challenge to launch a single staged liquid rocket to 100 kilometres. "We are just in the preliminary design stages of this rocket," says Howlader. "But the goal is to have our rocket reach 100 kilometres by the end of 2021 — and there's a $1-million prize on the line."

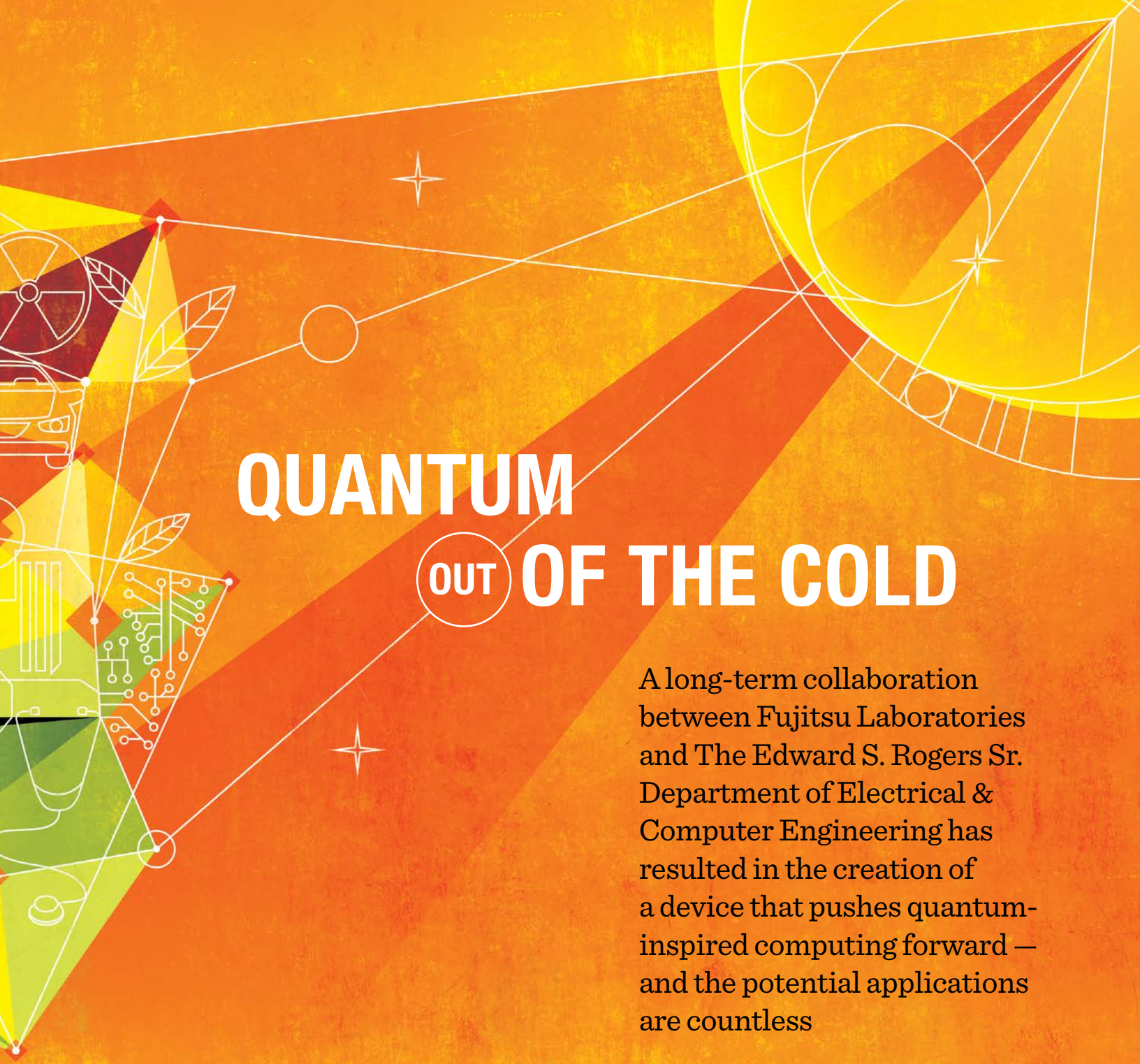
Most interesting for Howlader is the team's Outreach and Policy divisions. "I got involved with UTAT because the team came to my high school and got me participating before I was even thinking of university programs," says Howlader. "And I think that really influenced me and my path so I know how important that is."

More recently, the team has established a Space Policy Division to promote public policy related to the aerospace industry and national space operations. "We plan on advocating for improved legislation and initiatives within the federal government — legislation related to drone operation is just one example of where I think we can help to make sure policy is keeping pace with technology — so we will be drafting policy proposals and conducting research related to that," says Howlader. "But UTAT is also a partner of the United Nations Space Generation Advisory Council so our reach will continue to be international as well."

The Space Policy Division will have two major areas of focus for its advocacy efforts. The first is the use of space technologies for disaster management, which will be the focus of a policy proposal the team will submit to the Canadian Science Policy Centre. The second area of focus will be in human health in space. "We are working on a longer research effort on this topic," says Howlader. "We will submit our research for consideration for the 2019 International Astronautical Congress — which will coincide with the fiftieth anniversary of humans first walking on the moon."

After completing his third year of studies, Howlader is starting to think about where his career might take him after he steps down as UTAT Executive Director and graduates from ECE. "I want to go into an industry that is multidisciplinary and very high impact," says Howlader. "I feel like I'm getting this really interesting technical background here in ECE and I'm learning a lot of soft skills through UTAT; if I can leverage that to make an impact — that's where I want to go."

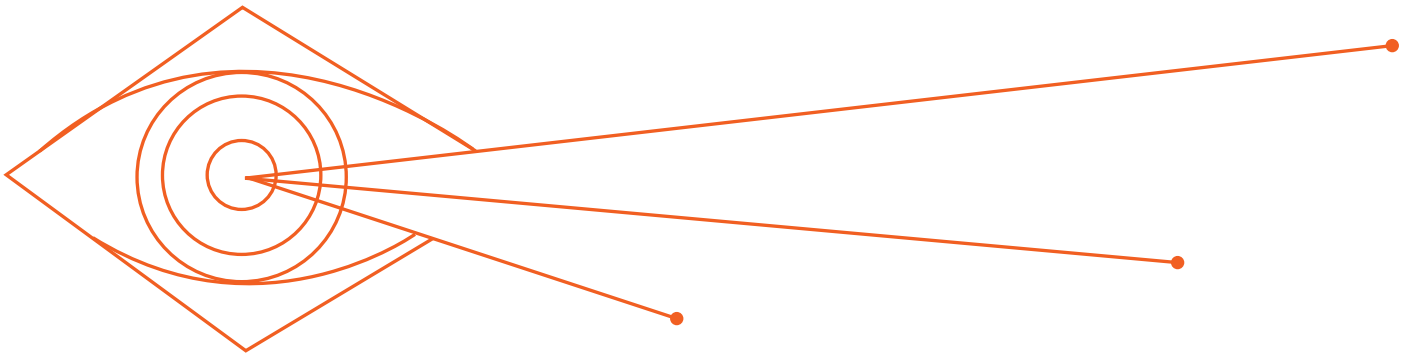
He knows he has a bit of time before he needs to decide his career path and the opportunities ahead of him are limitless: for Howlader, space is just the first frontier. A



QUANTUM OUT OF THE COLD

A long-term collaboration between Fujitsu Laboratories and The Edward S. Rogers Sr. Department of Electrical & Computer Engineering has resulted in the creation of a device that pushes quantum-inspired computing forward — and the potential applications are countless

BY JESSICA MACINNIS
ILLUSTRATION BY TRACI DABERKO



The internship was supposed to last for just six weeks.

As a graduate student in 1998, Professor Ali Sheikholeslami had a problem — he needed access to measurements of ferroelectric capacitors he was developing a model for. By chance, at a conference he met Dr. Hirotaka Tamura of Fujitsu Laboratories who could provide access to the measurements and was interested in learning more about Sheikholeslami's model.

A short internship was established: Sheikholeslami was to travel to Japan to work with the device in Tamura's lab just long enough to create a new model based on actual measurements.

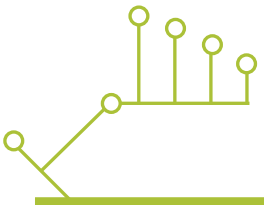
"Looking back on it, that was probably the most productive six weeks of my life," says Sheikholeslami. "During that time, I was able to come up with a new model that has been used extensively since, and we wrote the first paper on this topic that was submitted shortly after I returned." More importantly, Sheikholeslami and Tamura established a good working rapport and when Sheikholeslami was hired as a professor at The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE), Fujitsu initiated a formal collaboration with his research group. Originally a three-year agreement, it was extended to five years. "Once the original project ended, we started working on another problem," says Sheikholeslami. "And then another."

Twenty years later, Sheikholeslami continues to collaborate with Tamura and Fujitsu is establishing a new research laboratory at the University of Toronto. "Over two decades, we've worked on non-volatile memory technology — for use in contactless smart cards — and high-speed signalling," says Tamura. "Together we've published more than 30 research papers and our work has led to several patents, but most importantly we've worked on some really interesting problems."

By 2015, with the end of Moore's Law in sight, Fujistu was keen to continue to make performance improvements despite the slowdown in technology scaling. "At the time, Tamura and I talked a lot about the end of Moore's Law and what we could do to continue to move forward," says Sheikholeslami. "There were all of these problems that could not be easily solved using classical computers."

Many of these challenges can be expressed as large-scale optimization problems, where one is looking for the best answer from among an astronomically large number of candidate solutions.

The travelling salesperson problem is a classic example. On a sales trip travelling through 32 cities, what is the best route for the salesperson



The digital annealer that we have developed can solve optimization problems much faster than simulated annealers, and is quantum inspired. In fact, it rivals so-called quantum annealers.

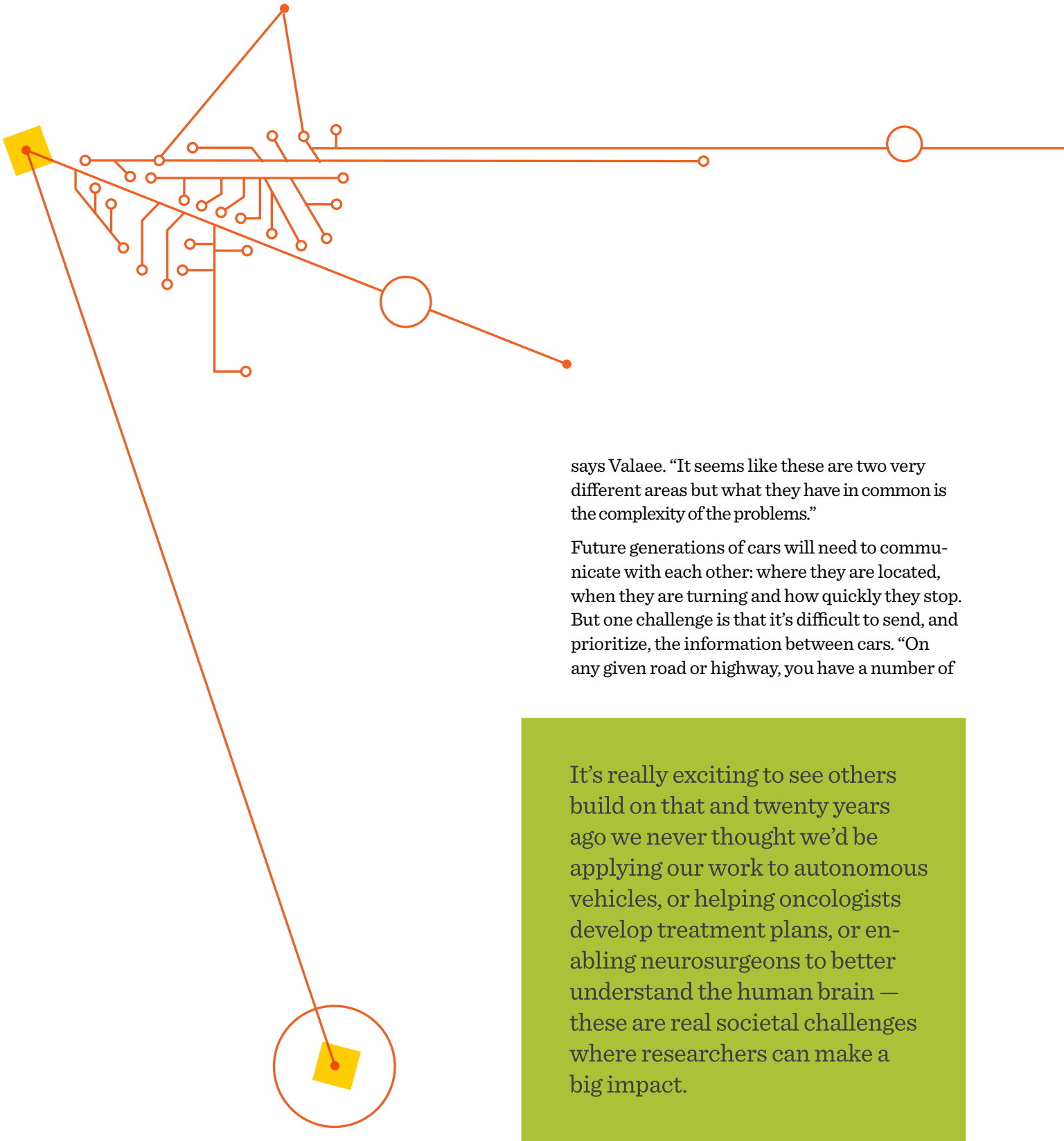
to take, in order to minimize the distance travelled? "If you start in any city, for your next stop you have 31 options and for the stop after that, 30 options," says Sheikholeslami. "The number of possible routes traversing all 32 cities is huge — in this case the number would be 34 digits long, and it really blows up for a larger number of cities. And only one of these routes gives you the minimum distance travelled." Large scale optimization problems like this have huge search spaces making them incredibly taxing to solve on classical computers.

Existing approaches to solve such problems involve running advanced software packages, e.g., simulated annealing, on large installations of standard computers. Sheikholeslami and Tamura decided to explore a route that combines advances in both hardware and software. Together, they developed hardware innovations, inspired by concepts from quantum computing, leading to what they call the digital annealer. "The digital annealer that we have developed can solve optimization problems much faster than simulated annealers, and is quantum inspired," says Sheikholeslami. "In fact, it rivals so-called quantum annealers." By approaching these problems in both hardware and software the two sought to speed up the computations while making it accessible to utilize on commercial computers.

Like a graphics card, the digital annealer fits into a regular computer but doesn't require programming. It also does not require the expensive and cumbersome cooling that quantum annealing demands but is still able to solve problems that are prohibitively expensive for classical computers to solve. "Quantum bits — or qubits — are based on the phenomenon known as 'superposition' which is the existence of two different states at the same time, in this case, zero and one," says Tamura. "The digital annealer draws on massive parallelism available in classical circuits to speed up its stochastic search of the solutions space."

The Fujitsu Co-Creation Research Laboratory at the University of Toronto was officially launched in March of 2018 at U of T Engineering's new Myhal Centre for Engineering Innovation & Entrepreneurship. The goal of this research hub on campus is to accelerate collaborative work in areas like quantum-inspired computing and machine learning while exploring application areas from medicine to smart cities.

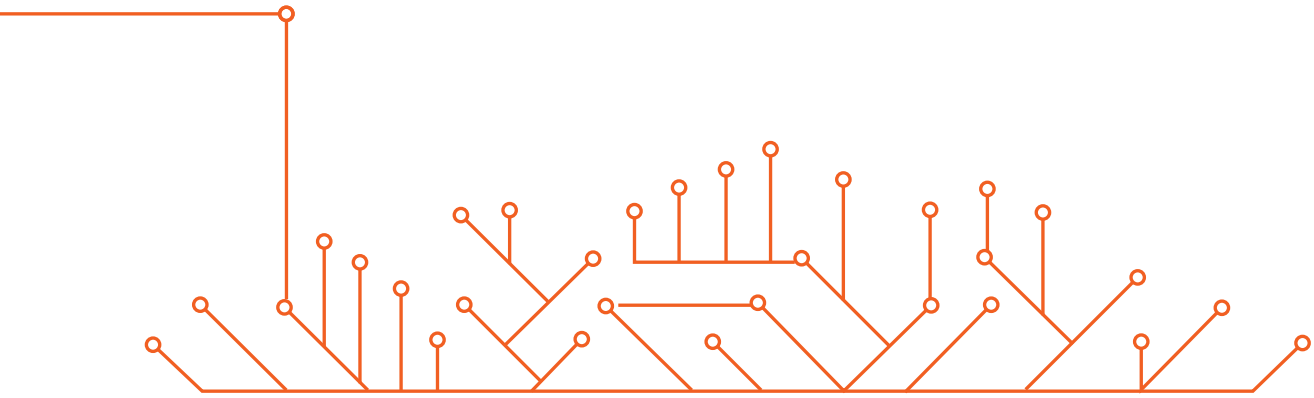
Professor Shahrokh Valaee is one of a few U of T researchers embarking on research collaborations with Fujitsu to apply the digital annealer to a myriad of complex societal challenges. "My team is working with Fujitsu on two main areas: machine learning for medical imaging and scheduling for communication between cars,"



says Valaee. “It seems like these are two very different areas but what they have in common is the complexity of the problems.”

Future generations of cars will need to communicate with each other: where they are located, when they are turning and how quickly they stop. But one challenge is that it’s difficult to send, and prioritize, the information between cars. “On any given road or highway, you have a number of

It’s really exciting to see others build on that and twenty years ago we never thought we’d be applying our work to autonomous vehicles, or helping oncologists develop treatment plans, or enabling neurosurgeons to better understand the human brain — these are real societal challenges where researchers can make a big impact.



cars that would need to communicate with each other. If two cars are sending information to each other by electromagnetic waves at the same time, the packets collide — so they have to take turns sending," says Valaee. "But this is a very complex problem: which car sends what information when? Especially when the network is distributed like a vehicular network."

Valaee and his team are using the digital annealer to find the best plan to execute car-to-car communication, which will be a new service in 5G cellular systems. Cars on the road today are extremely sophisticated. We have cars that have more than 100 microprocessors inside them — essentially, we are driving supercomputers. But there's a disconnect between the technology within the cars and the communication between them. "Currently, our car-to-car communications — whether it's brake lights, turning signals or car horns — are very rudimentary in comparison to the technology under the hood," says Valaee. "There's a lot of room to improve communication between cars and the digital annealer could hold the key. This is incredibly important for self-driving cars of the future, but could also be applied to today's vehicles."

Fujitsu is collaborating on other projects with ECE researchers, including Professor Al Leon-Garcia's work on integrating and interpreting the high volume of data generated and utilized by smart cities. "Smart cities are a ripe application area for the digital annealer," says Leon-Garcia. "Reams of data are being generated and there are many different ways in which we could interpret this data and integrate what we learn from it back into the smart city's systems. But to do this we need formidable computing engines and the digital annealer is one way to tackle these challenges."

While the problems the digital annealer can help to solve are complex, the partnership between Sheikholeslami and Tamura is decidedly simple: "The relationship established over a number of years with Professor Sheikholeslami has been one built on mutual respect, trust and very open communication," says Tamura. "It's really exciting to see others build on that and twenty years ago we never thought we'd be applying our work to autonomous vehicles, or helping oncologists develop treatment plans, or enabling neurosurgeons to better understand the human brain — these are real societal challenges where researchers can make a big impact." For Tamura, the establishment of the collaborative laboratory is an exciting step in the company's relationship with the University of Toronto, but it's also symbolic of the potential of what's ahead.

What started as a six-week internship has grown to nearly two decades of collaboration between Fujitsu and the University of Toronto, with multiple researchers and research areas involved. "But every time we begin a new project or look at a new problem together it feels like we are just getting started," says Sheikholeslami. "There's lots of exciting work ahead." A

Undergraduate Study

TRAINING THE NEXT PROBLEM SOLVERS

Behind advances in technology, business, medicine and beyond, you'll find electrical and computer engineers using math and science to solve problems and create innovative new products. An undergraduate degree from The Edward S. Rogers Sr. Department of Electrical & Computer Engineering opens doors to any career imaginable, from app development to artificial intelligence, mechatronics to medicine, and every field in between. The first two years of the ECE program are common to both electrical and computer engineering students, and provide essential background in basic science and mathematics, as well as introducing important concepts in electrical and computer engineering such as circuits, digital systems, electronics and communication systems. In third and fourth year, students choose areas of specialization depending on their individual strengths and interests. Options include biomedical engineering, mechatronics and systems control, software and hardware engineering, energy systems, digital and analog electronics, electromagnetics, photonics, and communications. Our flexible curriculum is the preferred choice for students seeking the opportunity to create their own unique paths of study, and to work alongside professors who are world-renowned experts in their fields. Learn more about the flexible curriculum at **uoft.me/ececurriculum**.

16:1
Undergraduate student-to-faculty ratio in ECE

Undergraduate degrees awarded, 2017-2018

ElecE *94*
CompE *209*
Total *303*

PHOTO BY ROBERTA BAKER

U OF T ENGINEERING LAUNCHES ARTIFICIAL INTELLIGENCE MINOR AND CERTIFICATE

Recent advances in electrical and computer engineering, as well as in computer science, have enabled the explosion of artificial intelligence (AI) technologies and applications. Innovations in sensors, data collection and storage, software and hardware have all contributed to the practical application of artificial intelligence in areas like medicine, law and communications.

Beginning in January 2019, students in the Faculty of Applied Science & Engineering will have the opportunity to complete a minor or certificate in AI to help them prepare to drive innovations in the field beyond graduation.

To complete the minor, students will need to take the equivalent of six half-year courses that explore machine learning (ML) and AI concepts, including a new course in AI fundamentals. Courses also delve into topics such as data mining, neural networks and deep learning. The certificate requires three half-year courses. Both the certificate and the minor in AI are open to U of T Engineering undergraduate students in all disciplines and all years.

STARTING AT THE TOP

In 2018, Mirza Nahiyan (Year 1 CompE) was one of seven students from the Toronto District School Board to receive a 99 per cent or higher average in their last year of high school. *ANNUM* sat down with Mirza to hear about why she chose The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE) and about her experiences as a first-year student so far.

Q: IN GRADE 12, YOUR AVERAGE WAS 99 PER CENT — WAS THIS SOMETHING YOU SET OUT TO ACCOMPLISH?

A: No, marks were never really my focus because I didn't see the advantage in fixating on a number. If you are focused on a specific grade, you are either limiting yourself or expecting too much of yourself. I just figured you should always just try your best and if you tried your best you wouldn't regret it.

Q: WHAT DREW YOU TO ELECTRICAL AND COMPUTER ENGINEERING?

A: In my family, we always joked that I was "tech support" — they would ask me to fix anything that came up with their phones or computers. But the truth is, I've always loved working with and learning about technology. It's always been something I have wanted to pursue, so I felt like it was the perfect fit for me when I was choosing what to do in university. From pretty early on I knew what I wanted to study: computers and software.

Q: WHY ECE AT THE UNIVERSITY OF TORONTO?

A: Before deciding, I had visited campus a number of times and learned that there were so many resources here for students. I had visited here for campus tours, met professors and students, and really felt at home here. I loved the campus and thought electrical and computer engineering would be the best fit for me because even though right now I'm interested in software, this department would give me an excellent background in both software and hardware.

Q: WHAT'S BEEN THE HIGHLIGHT OF YOUR TIME AS A FIRST YEAR ECE STUDENT SO FAR?

A: Definitely the people. There's a real sense of community here. I was worried it would be competitive but there are so many resources and everyone really tries to help each other out. You can walk up to anyone in your class and talk about the course that you are in and you can help each other. There's so many opportunities to get help — if you need help you can find it. I've already gone to so many help sessions, office hours, met with TAs and been to tutorials. There's so much support and you actually feel cared for.

Q: ANY ADVICE FOR STUDENTS IN HIGH SCHOOL?

A: Everybody learns differently, but people get caught up in the marks and they lose sight of what is important, which is the entire process of learning. If you focus on learning and really fall in love with learning, then everything else just comes more naturally.

$89,360

Top salary earned by an ECE student on PEY Co-op placement in 2018-2019

PROFESSIONAL EXPERIENCE YEAR CO-OP PROGRAM (PEY CO-OP):

In 2018, U of T's Professional Experience Year (PEY) Co-op Program celebrated its 40th anniversary. It's the largest program of its kind in Canada, and PEY Co-op companies represent every sector and include major global brands such as Apple, Tesla, Google and IBM. This optional program enables undergraduates who have completed their second or third year of study to build meaningful work experience, strengthen their professional networks and enhance their interpersonal and technical competencies. During this period, which lasts 12 to 16 consecutive months, students are full-time employees with a competitive salary.

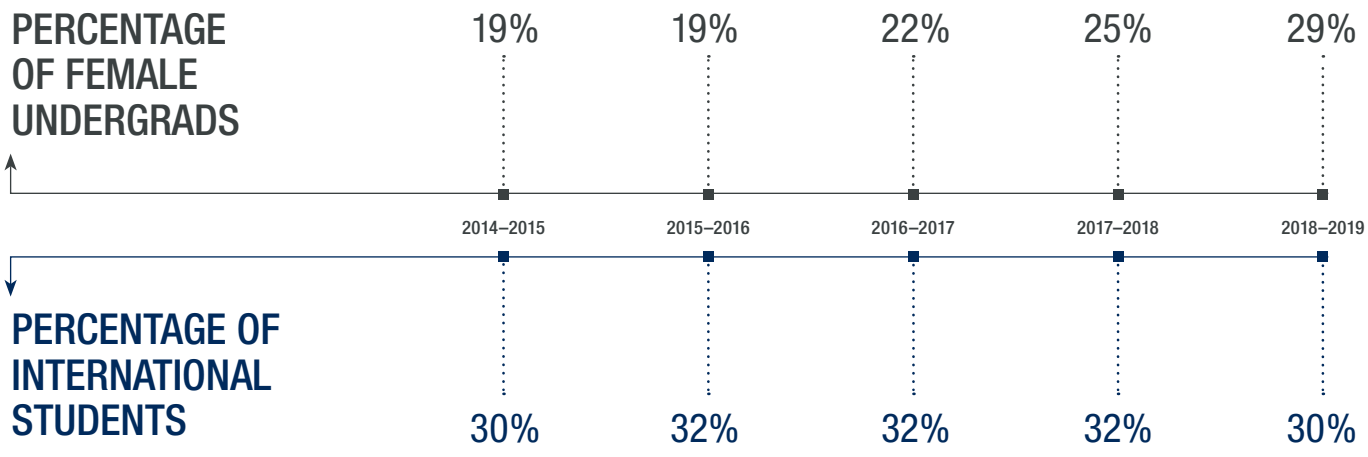
In 2018–2019, 264 ECE students are working in PEY Co-op work terms at 109 companies located across Canada and around the world, earning an average salary of $53,132. To learn more, visit **uoft.me/ecepeyco-op.**

UNDERGRADUATE ENROLMENT, 2014–2015 TO 2018–2019

	PART TIME	FULL TIME	TOTAL
2014-2015	272	1208	1480
2015-2016	313	1199	1512
2016-2017	283	1230	1513
2017-2018	289	1198	1487
2018-2019	324	1216	1540

ECE PEY CO-OP PLACEMENTS, 2013–2014 TO 2017–2018

	ElecE	CompE	TOTAL
2014-2015	156	70	226
2015-2016	160	92	252
2016-2017	135	91	226
2017-2018	121	120	241
2018-2019	127	137	264



Graduate Study

AN INTERNATIONAL DESTINATION

The Edward S. Rogers Sr. Department of Electrical & Computer Engineering has borne witness to groundbreaking discoveries and developments in almost every area of electrical and computer engineering — at the core of these advances is the outstanding research conducted by graduate students and faculty members. Graduate students in ECE choose from a wide variety of research areas including biomedical engineering, communications, computer engineering, electromagnetics, electronics, energy systems, photonics and systems control. They are supervised by our faculty of 79 professors, many of whom are internationally recognized leaders in their fields. We offer three degrees: Master of Engineering (MEng), Master of Applied Science (MASc) and Doctor of Philosophy (PhD). For program and admissions information, visit **uoft.me/ece-gradadmission**.

$2.6M
in graduate student scholarships awarded by ECE for 2018-2019

OUR GRADUATE STUDENTS BY FIELD OF STUDY

	MASC	PHD	TOTAL
BIOMEDICAL	11	1	**12**
COMMUNICATIONS	41	53	**94**
COMPUTER	60	49	**109**
ELECTROMAGNETICS	13	22	**35**
ELECTRONICS	27	35	**62**
ENERGY SYSTEMS	20	23	**43**
PHOTONICS	19	44	**63**
SYSTEMS CONTROL	7	7	**14**

INTRODUCTIONS: GRADUATE STUDENTS AND INDUSTRY CONNECT AT NETWORKING RECEPTION

In September, The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE) and the ECE Graduate Student Society (ECEGSS) co-hosted a networking reception at the University of Toronto's Hart House to connect graduate students with representatives from leading Canadian and international companies.

More than 150 graduate students, employers and professors gathered to network and discuss potential employment opportunities for graduate students looking to pursue research in industrial settings after graduating. Employers connected with students and spoke about general areas of interest, specific roles they were looking to fill and learned about graduate students' specific research projects and experience.

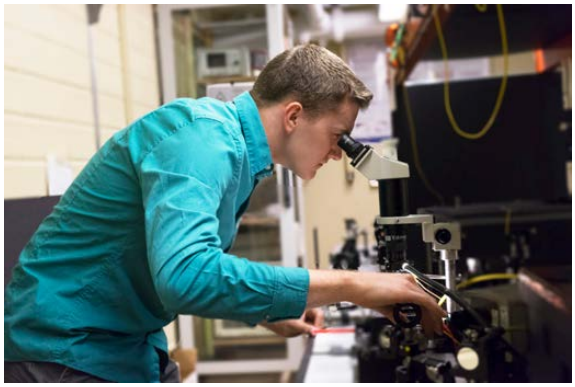
"The reception was a really great opportunity for students to talk about their research and learn how their skills and experience could be leveraged in a non-academic setting," said co-organizer Karthik Ganesan (ECE PhD candidate). "We really wanted to make sure that there were not just recruiters in the room, but technical employees who could speak to the work they were doing and what technical expertise they were looking for too — and I think we accomplished that."

TWO ECE GRADUATE STUDENTS AWARDED $150K VANIER SCHOLARSHIPS

Two graduate students from The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE) were named 2018 recipients of the prestigious Vanier Canada Graduate Scholarships. Worth $50,000 per year over three years, the Vanier Scholarship recognizes doctoral students at Canadian universities who demonstrate excellence in academics, research impact and leadership.

Surath Gomis (ECE PhD candidate) works under the supervision of Professor Ted Sargent (ECE) and co-supervisor Professor Shana Kelley of the Leslie Dan Faculty of Pharmacy. As part of a collaborative team in U of T's Medicine by Design, Gomis's work focuses on designing microfluidic devices to characterize and sort retinal stem cells — a rare cell type with promising therapeutic applications of reversing blindness due to degenerative eye disease.

"This recognition encourages me to think outside of the box and to continue tackling challenging problems in engineering and medicine," says Gomis. "I would like to thank Professor Sargent and Professor Kelley for their immense support through my early graduate career, and all my colleagues and mentors from the years past who have supported my aspirations in the field."



Trevor Stirling (ECE PhD candidate) studies under the supervision of Professor Amr Helmy (ECE), working on the design and implementation of entangled photon lasers on silicon-based computer chips. These devices will be used to interconnect quantum bits on chip to help realize scalable quantum computing, as well as provide a platform for further research into the applications of quantum light. In addition to his studies, Stirling is a competitive athlete — he has represented Canada in trampoline at international competitions around the world.

"It is a great honour to be selected as a Vanier scholar and that my research under Professor Helmy has been acknowledged to have the potential to make an impact within Canada and around the world," says Stirling. "Receiving this award will allow me the freedom to pursue my research interests, and to continue to train and compete in the sport of trampoline."

TOTAL GRADUATE ENROLMENT, 2014–2015 TO 2018–2019 (HEADCOUNT)

	FALL 2014	FALL 2015	FALL 2016	FALL 2017	FALL 2018
MASC	173	145	158	191	198
PHD	253	245	242	212	234
MENG	169	249	249	209	226
TOTAL	595	639	649	612	658

GRADUATE DEGREES AWARDED, 2013–2014 TO 2017–2018

	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018
MASC	70	71	70	53	69
PHD	27	35	47	38	49
MENG	85	76	97	144	101
TOTAL	182	182	214	235	219

Enrolment in Research-stream Programs 2018–2019

MASc 198

PhD 234

Total 432

Research

A CONCENTRATION OF POWERFUL MINDS

Researchers in The Edward S. Rogers Sr. Department of Electrical & Computer Engineering tackle challenging fundamental and applied problems of importance to global industry and society. We work across and beyond disciplinary boundaries to advance current understanding in key emerging areas such as smart-grid technology, mobile and cloud computing, and biomedical engineering. Our department alone occupies more than 4,500 square metres of research laboratory space across six buildings on University of Toronto's downtown St. George Campus. We also house the Toronto Nanofabrication Centre, home to several state-of-the-art nanofabrication facilities that are available to both academic and industry clients for open access prototype development and testing. As one of the largest ECE departments in Canada, we are a research powerhouse. Our professors partner with countless industry leaders worldwide to stimulate, enhance and translate our research into application. We continue to seek opportunities to collaborate with industry, government and other academic institutions to improve quality of life in Canada and around the globe. Learn more about how research in ECE is shaping the world at **uoft.me/eceresearch**.

$340K – AVERAGE ANNUAL RESEARCH FUNDING PER ECE FACULTY MEMBER

Our Faculty by Research Group

BIOMEDICAL ENGINEERING **6**
COMMUNICATIONS **16**
COMPUTER ENGINEERING **20**
ELECTROMAGNETICS **6**
ELECTRONICS **9**
ENERGY SYSTEMS **9**
PHOTONICS **8**
SYSTEMS CONTROL **5**
EMERITUS **20**

TOTAL 99

SELECTED AWARDS WON BY ECE FACULTY, 2017-2018

INSTITUTE OF ELECTRICAL & ELECTRONICS ENGINEERS, FELLOW // **Professor Ben Liang**
AMERICAN PHYSICAL SOCIETY, FELLOWS // **Professors Nazir Kherani and Hoi-Kwong Lo**
OPTICAL SOCIETY (OSA), FELLOWS // **Professors Amr Helmy and Hoi-Kwong Lo**
CANADIAN ACADEMY OF ENGINEERING, FELLOW // **Professor Frank Kschischang**
ASSOCIATION FOR COMPUTING MACHINERY, DISTINGUISHED MEMBER // **Professor Natalie Enright Jerger**
CONNAUGHT INNOVATION AWARD // **Professor Andreas Moshovos**
CONNAUGHT GLOBAL CHALLENGE AWARD // **Professor Andreas Veneris**
SAFWAT ZAKY RESEARCH LEADER AWARD // **Professor George Eleftheriades**
MCCHARLES PRIZE FOR EARLY CAREER RESEARCH DISTINCTION // **Professor Ding Yuan**

KSCHISCHANG AND YOUSEFI WIN 2018 IEEE INFORMATION THEORY SOCIETY PAPER AWARD

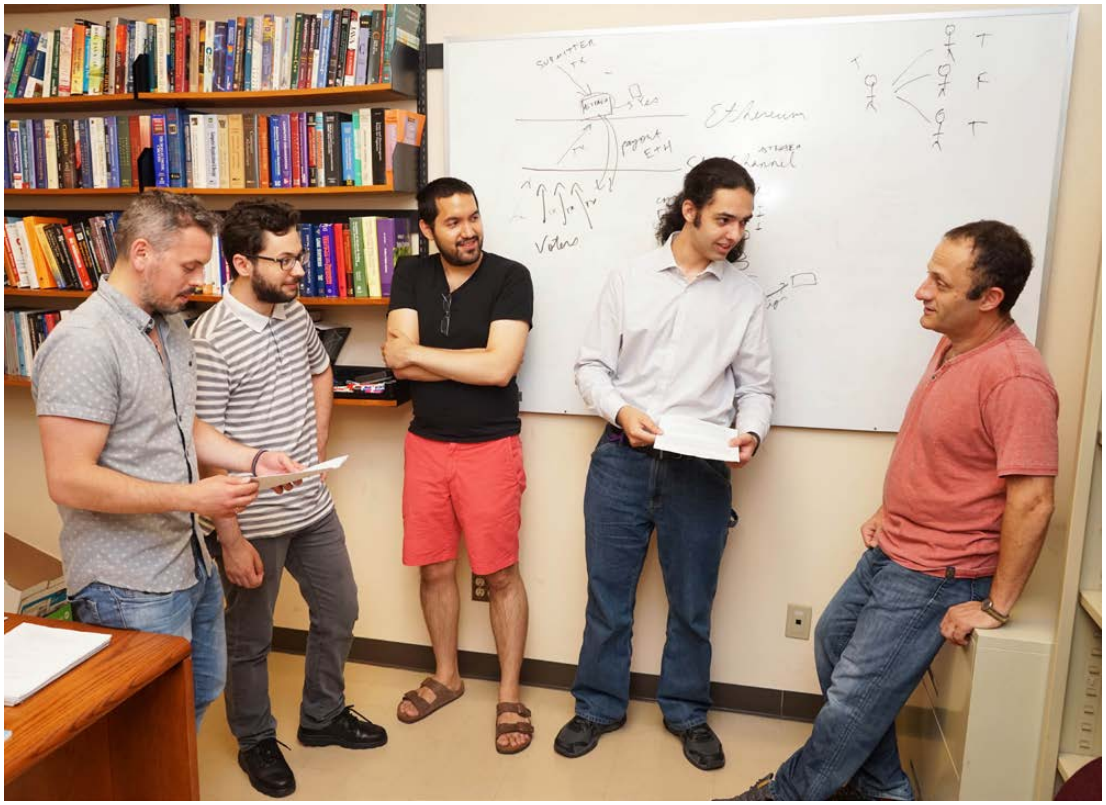
The vast majority of the world's Internet and long-distance telecommunications is carried over fibre-optic networks that criss-cross the continents and span between them via ultra-long undersea cables. One challenge for researchers is that the information-carrying capacity of these optical fibres remains unknown: information theorists are not yet sure if we are squeezing as much capacity out of optical fibres as we possibly can.

The theoretical difficulty in establishing the capacity of optical fibres is that, at the very high optical intensities needed to send information quickly over vast distances, the fibre-optic channel is a nonlinear medium. The so-called optical Kerr effect causes the index of refraction of the silica glass material of a fibre to change in response to the intensity of the light propagating within it. The resulting mathematical channel model goes far beyond well-studied textbook models.

Professor Frank Kschischang's research group is working on determining the information-theoretic limits of optical fibre networks. In 2014, Professor Kschischang and his former student, Dr. Mansoor Yousefi (ECE PhD 1T3), published a three-part paper titled "Information Transmission using the Nonlinear Fourier Transform, Parts I—III," in which they describe a new transmission scheme that is inherently compatible with the fibre non-linearity and which has the potential to achieve gains over conventional methods.

For their work, they received the 2018 IEEE Information Theory Society Paper Award at the IEEE International Symposium on Information Theory in June of 2018. The Information Theory Society Paper Award is given annually to an outstanding publication in the field. It recognizes papers that stimulate interest in and encourage contributions to fields of interest of the Society.

"Encoding information in the nonlinear spectrum allows us to reduce the influence of fibre non-linearity, providing us with the potential to achieve greater data rates than today's systems," says Kschischang. "It's a great honour to be recognized by our peers and it's exciting to see that there are several research groups around the world who are testing this method and developing it further."



You can bank on it: ECE professor leads UTLedgerHub for crypto-economic blockchain technology

Blockchain technology has the potential to overhaul the way we carry out transactions, execute contracts and vote in civic elections.

But the development of this technology is happening outside of the mainstream tech sector, with universities and their researchers largely on the sidelines. A project led by Professor Andreas Veneris, of The Edward S. Rogers Sr. Department of Electrical & Computer Engineering aims to change that.

Professor Veneris received $250,000 from the Connaught Global Challenge Award to create the UTLedgerHub, the University of Toronto's global knowledge hub for crypto-economic blockchain technology.

The UTLedgerHub will unite researchers across a wide range of fields to establish U of T as an international leader in research and teaching of decentralized ledger technology and help cement Toronto as a leader in the field at a global scale.

"The area of blockchain research is not simply a technology issue," said Veneris. "The impact of how we develop and implement these innovations extends well beyond electrical and computer engineering and into law, economics, public policy and social justice."

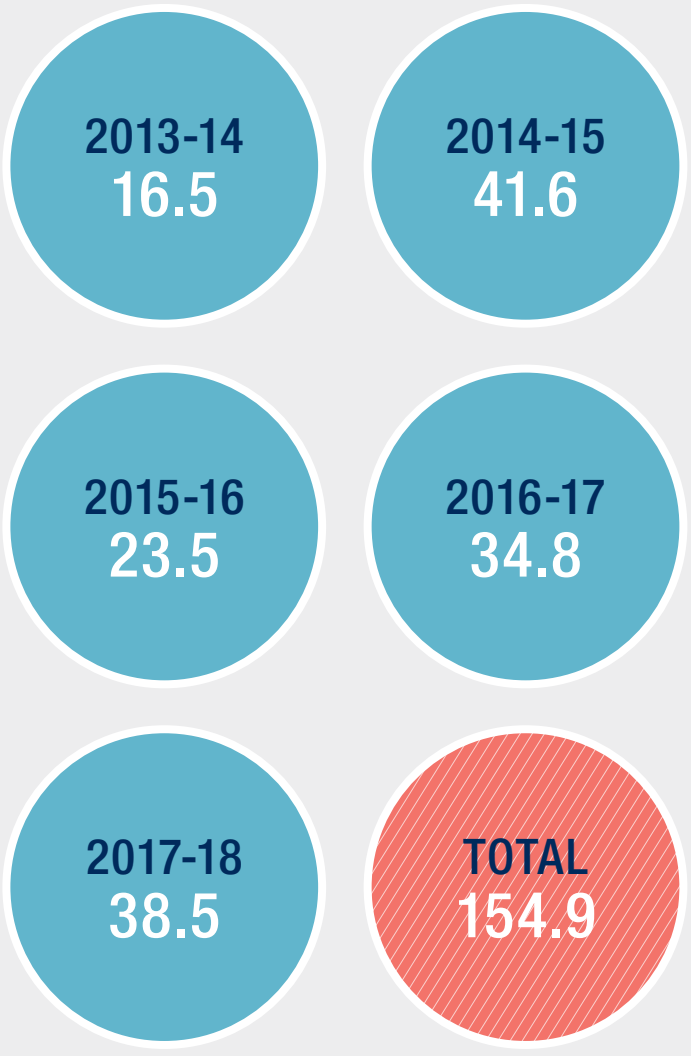
His team includes U of T researchers Andreas Park from the Rotman School of Management; Jon Lindsay from the Munk School of Global Affairs & Public Policy; Katya Malinova from the department of economics, as well as Poonam Puri from Osgoode Hall Law School at York University.

ECE RESEARCH FUNDING 2012–2013 TO 2016–2017

	FEDERAL	PROVINCIAL	INDUSTRY	OTHER	TOTAL $
2012-2013	9,861,957	2,300,498	2,305,784	3,590,130	**18,058,369**
2013-2014	11,668,423	3,310,688	3,226,004	4,283,350	**22,488,465**
2014-2015	14,659,734	4,906,558	3,176,267	2,112,100	**24,854,659**
2015-2016	14,358,107	4,042,251	2,998,980	2,369,957	**23,769,295**
2016-2017	13,322,501	4,016,933	4,860,989	2,289,940	**24,490,363**

ECE INVENTIONS DISCLOSED OVER THE PAST FIVE YEARS

In cases of cross-disciplinary inventions, disclosures are expressed as a fraction



ECE is the top U*of*T department over the past five years for new invention disclosures, new patent applications filed and new license and option agreements executed.

Industry Partnerships

TACKLING REAL-WORLD PROBLEMS

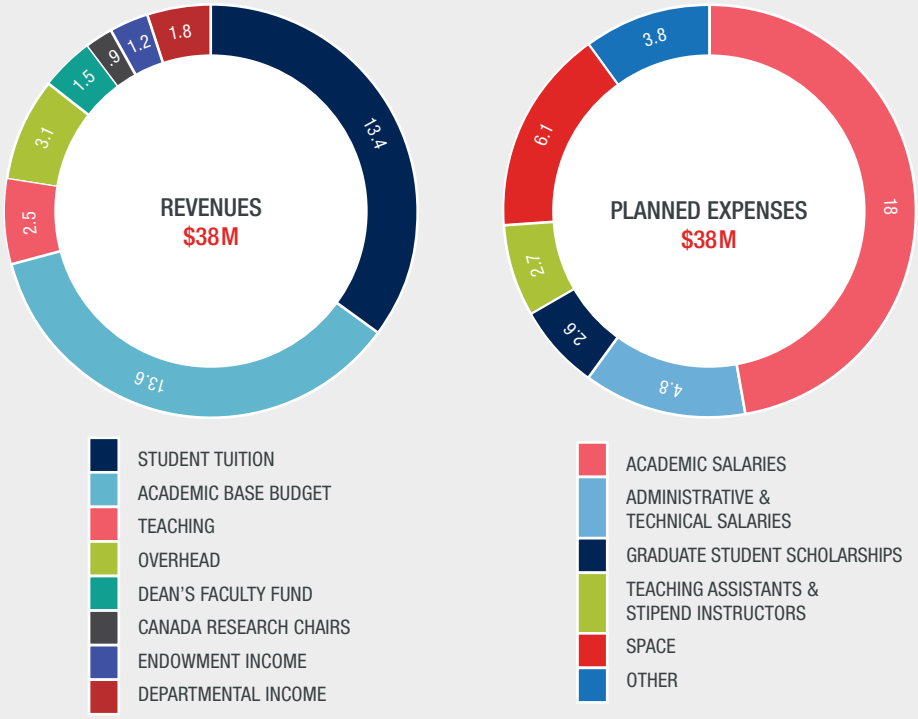
In The Edward S. Rogers Sr. Department of Electrical & Computer Engineering, we pride ourselves on cultivating both longstanding and new partnerships with visionary corporations, foundations and institutes the world over. These ties keep our research relevant, our teaching fresh, and continually inspire us to find multidisciplinary solutions to technological, economic and social problems both here in Canada and abroad. Over the past five years we've had partnerships with more than 85 industry funders and collaborators.

In November, Fujitsu Labs Ltd. was named the 2018 Corporate Research Partner of the Year by U of T Engineering. This award celebrated Fujitsu's long standing partnership with ECE and recognized the growth of the partnership through the Fujitsu Co-Creation Research Laboratory at the University of Toronto. This multidisciplinary research hub will accelerate collaborative work in fields including machine learning, quantum-inspired computing, smart cities, advanced health care and financial technology. Learn more about upcoming events at **uoft.me/eceevents**.

ECE accounts for more than 40% of all U *of* T Engineering invention disclosures

WHERE THE MONEY GOES:

OUR 2018-2019 FINANCIAL PICTURE AT A GLANCE ($ MILLION)



THREE ECE PROFESSORS NAMED VECTOR INSTITUTE FACULTY AFFILIATES

Professors Jason Anderson, Vaughn Betz and Andreas Moshovos of The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE) are among 63 Faculty Affiliates from nine Ontario institutions that comprise the 2018 cohort of Vector Institute Faculty Affiliates.

Affiliates were selected based on recommendations from a committee of Vector Faculty members who reviewed applicants based on the strength of their research contributions and the alignment of their research interests with the Vector Institute. ECE's Professor Brendan Frey is a founding member of the Vector Institute.

Professor Anderson's research group is looking at implementing machine learning algorithms on reconfigurable integrated circuits called Field Programmable Gate Arrays (FPGAs) to achieve higher energy efficiency than standard processors.

Professor Betz's group is working on making efficient programmable hardware accelerators for deep learning using current FPGAs, and also improving the architectures of these programmable chips to make them more effective accelerators for deep learning.

Professor Moshovos heads the NSERC Strategic Partnership Network in Computer Hardware for Emerging Sensory Applications (COHESA) — a national research network that aims to create the next generation of computing engines optimized for artificial intelligence.

The Vector Institute was founded in 2017 to attract, retain and train talent in the field of artificial intelligence. Vector Faculty Affiliates will play a key role in developing, growing and diversifying knowledge and research within the AI community, including both researchers and industry. Faculty Affiliates will have access to the Institute's programming and are appointed for two year terms with nominations considered annually.

$18.7 M

Corporate funding to ECE over the past five years

229 Employers Hiring ECE Students on PEY Co-op Over the Past Five Years:

2mpower
407 ETR Concession Company Ltd.
AB SciEx (formerly MDS Sciex)
Accenture
Acuity Ads
Aercoustics Engineering Limited
AeroFS
AGFA Graphics NV-Belgium
AiQi Information Technology Company
Altera
Amazon
AMD
AMD Shanghai
Ampex Japan Ltd.
Analog Devices
AnalogX Inc.
Apple
Aquantia Canada Corp.
Arista Networks
Arup
Bayer Healthcare
Behaviour Interactive
Bell
Bell Mobility
Bibliocommons Inc.
Big Viking Games
Blackberry Limited
Bluecat
BMW Group Canada
Caine Health Inc.
CaseWare International Inc.
CAST Software Inc.
Celestica Inc.
Ceridian Canada LTD.
CGI Group Inc.
CIBC
Ciena
CiRBA Inc.
Cisco Systems Inc.
City of Brampton
Communications and Power Industries Canada Inc.
Conavi Medical Inc.
CONTAX Inc.
DAC Group
Deloitte
Deloitte & Touche LLP
DEMONWARE
Desire2Learn
Dessa (formerly DeepLearni.ng)
Destiny Solutions
Doublethink Inc. (myBlueprint)
DPM Energy
Drone Delivery Canada
Eastern Power
eCAMION
Edward S. Rogers Sr. Department of Electrical & Computer Engineering
Enersource Hydro Mississauga
Enerva
Environment and Climate Change Canada
Environment Canada
Envision Mobile
Epson
Equifax
Ericsson Canada Inc.
Esna Technologies
EventMobi
Evertz Microsystems Ltd.
FinanceIt Canada Inc.
Finastra (formerly D+H)
Fio Corporation
Ford of Canada
Forma AI Inc.
Fu Tin Business Co. Ltd.
FureVault Inc.
General Electric
General Electric Canada
General Motors of Canada
Genesys Canada Laboratories Inc.
Geo Semiconductor Inc.
GGY a Moodys Analytics Company
Google
Hatch
Healthcare of Ontario Pension Plan
Honda
Honeywell
Huawei Technologies Canada, Co., Ltd.
Husky Injection Molding Systems Ltd.
Hydro One
IBI Group
IBM
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Imagine Communications
IMRSV Data Labs
Indigo Books and Music
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Intact Financial
INTEL (formerly Altera Corporation)
Intelliware Development Inc.
iNTERFACEWARE Inc.
Intronix Technologies Corp.
Intuit Canada
Isowater Corporation
ITDG
Just Energy
Kapsch TrafficCom Canada Inc.
Kijiji
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Knowtions Research
L-3 Wescam
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Microsoft
Ministry of Children and Youth Services
Ministry of Education
Ministry of Transporation
ModiFace
Mold-Masters Ltd.
Moneris
Morgan Solar
Morgan Stanley
National Bank Financial Markets
National Research Council Canada
NexJ Systems Inc.
Nobul Coporation
NVIDIA
NXM TECHNOLOGIES INC.
NXP
Omnivex Corporation
Ontario Financing Authority (OFA)
Ontario Ministry of Education
Ontario Ministry of Health & Long-Term Care
Ontario Power Generation
Ontario Teachers Pension Plan (OTPP)
Oracle
Palantir Technologies Inc.
Patheon, part of Thermo Fisher Scientific
Peraso Technologies, Inc.
Periscope Capital Inc.
Perspecsys
Philips (China) Investment Co., Ltd.
Pivotal
PocketHealth
PrecisionHawk
Procter and Gamble
Proofpoint Inc.
PwC
QNX
Qualcomm
Quanta Technology
QuickTapSurvey
Rambus
Rapyuta Robotics Co., Ltd.
RBC
RBC Capital Markets
Red Hat Canada Ltd.
Rockwell Automation
Rubikloud Technologies Inc.
Samsung
Sandvine
Sanofie Pasteur Canada
SAP Canada Inc.
SAP Labs, LLC
SciCan
Sciyon Automation Groups
Scotiabank
SeamlessMD
Security Compass
Semtech
Siemens
Smith and Andersen Consulting Engineering
SOTI Inc.
Southpay Technology Inc.
Statflo
Strategic Mapping Inc.
Suncor Energy
SurfEasy
Swish Labs
Symantec
Synaptive Medical
Synopsys
Teck Resources Ltd.
Telus
Temenos
Thales
Thales Rail Signaling Solutions
The Hospital for Sick Children
TheRedPin.com Realty Inc.
Think Research
Thomson Reuters
TimePlay
Tofun Marine Supply Inc.
Toronto Hydro
Toronto Transit Commission (TTC)
TradeRev (formerly NthGen Software)
TransCanada
Transnomis Solutions Inc.
Trapeze Group
Tulip Retail
TunnelBear Inc.
TXIO
Tyco Electronics Canada ULC
UBER
Ultimate Software
University of Toronto - Mechanical and Industrial Engineering
Upstream Works Software
Validus Research Inc.
Veeva Systems
Veoneer Canada Inc. (formerly Autoliv)
Verity Studios
Wattpad
Wealthfront
WinMagic Data Security
Wuhan Blue Sea Technology and Innovation Co., Ltd.
Xagenic Inc.
Xilinx Inc.
XLV Diagnostics Inc.
Zebra Technologies (formerly Motorola Solutions)

ECE INDUSTRY ADVISORY BOARD

The Edward S. Rogers Sr. Department of Electrical & Computer Engineering formed its Industry Advisory Board in 2014. The board provides ECE with objective advice about the department's role in contributing to technological and economic development, and engineering practice. Its members are:

I-CHENG CHEN, FELLOW, PLATFORM ARCHITECTURE // AMD
SAI-KIT ENG, DIRECTOR OF PROGRAM MANAGEMENT // QUALCOMM
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ALLEN LALONDE, SENIOR INNOVATION EXECUTIVE // IBM CANADA
SONG ZHANG, DIRECTOR, TECHNOLOGY PLANNING & PARTNERSHIP // HUAWEI CANADA

HOW TO MULTIPLY YOUR MONEY

In ECE, we leverage industry financial support with federal, provincial and institutional matching to enable millions in industry-partnered research per year. A $52,500 industry contribution to a research project grows to $202,500—a 4x leverage on the initial investment.

$52,500 *industry investment* →

$202,500

leveraged 4x

The outcome: a joint project with the support of world-renowned researchers, expert administration, project management and motivated graduate students.

Contact us to explore the vast potential of partnering on research and technology development.

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416 978 7890

ADRIANO VISSA, PHD
ASSOCIATE DIRECTOR, CORPORATE PARTNERSHIPS
ADRIANO.VISSA@UTORONTO.CA
416 946 5004

ECE CORPORATE PARTNERS, 2014-2018

A.U.G. Signals Ltd.
ABB AB
Advanced Micro Devices Inc.
Altera Corporation
Analog Devices Inc.
Apple Inc.
Asahi Glass Co., Ltd.
Avertus Epilepsy Technologies Inc.
Bell Canada
BLiNQ Networks Inc.
Broadcom Corporation
Candura Instruments
Christie Digital Systems Canada Inc.
Ciena Canada Inc.
Dana Canada Corporation
Diros Technology Inc.
E. I. du Pont Canada Company
eCamion Incorporated
Ericsson Canada Inc.
ExtentCom Systems Inc.
Finisar Corporation
Ford Motor Company of Canada Ltd
Fuji Electric Co., Ltd.
Fujitsu Laboratories Ltd.
Fujitsu Labs of America, Inc.
Futurebound Corp.
Futurewei Technologies Inc.
Gener8 Inc.
Hatch Ltd.
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Huron Digital Pathology
Hydro One Networks Inc.
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Toshiba Corporation
Total American Services Inc.
Unisearch Associates
Varilume Lighting Inc.
Wurth Elektronik eiSos GmbH & Co. KG
Xilinx Inc.

Alumni

STRENGTH OF THE ECE ALUMNI NETWORK

The ECE alumni community is a powerful global network of leaders in a variety of fields ranging from entrepreneurship to sustainable energy, aerospace to artificial intelligence. ECE alumni are extremely generous with their time, and many volunteer to help current students — by meeting fourth-year students on the brink of graduation at our spring Fourth-Year & Alumni Reception, by sharing stories of startup successes and failures as part of our Engineering Entrepreneurship Speaker Series or through mentoring students in ECE CONNECT, our online alumni engagement platform. We value input from our alumni on our evolving priorities and direction, and we like to know where our graduates are now! If you have a piece of news you'd like to share, thoughts on our performance, or would like to hear how to get involved with your fellow alumni or current students, we'd love to hear from you. Contact senior communications officer Jessica MacInnis at eceinquiry@utoronto.ca or 416 978 7997. Stay in touch with your fellow alumni at **uoftececonnect.ca**.

More than 12 thousand active alumni worldwide

ECE alumni celebrated at U of T's Arbor Awards ceremony

Created in 1989, the Arbor Awards recognize University of Toronto volunteers for their outstanding personal service to the university.

This year, three ECE alumni and friends received Arbor Awards for their dedication to the university and for their contributions to the experience of U of T students, faculty, staff and alumni. Congratulations Jean Hiivala, Somen Mondal (CompE 0T2) and Kwong Wah Er (ElecE 7T0).

2018 ECE ALUMNI BOARD OF ADVISORS:

JOHN EAST
ElecE, MBA UC Berkeley
Former CEO of Actel Corporation

ALEX GRBIC
CompE 9T4, MASc 9T6, PhD 0T3
Chief Technology Officer at Omnia AI

CATHERINE LACAVERA
CompE 9T7, JD/MBA U of T
Director, Litigation at Google

NATASHA LALA
CompE 9T8
COO at ApplePie Capital

SOMEN MONDAL
CompE 0T2, MBA Queen's University
Co-founder and CEO of Ideal.com

ALEX SHUBAT
ElecE 8T3, MASc 8T5, PhD Santa Clara, MBA Stanford
Co-founder and CEO of Espresa

ECE DONORS FOLLOW THEIR HEARTS

As an alumnus of The Edward S. Rogers Sr. Department of Electrical & Computer Engineering (ECE), it wasn't until he retired after more than 43 years at Canada Wire and Cable (now Nexans Canada) that Lauri Hiivala (ElecE 6T5) looked back on his undergraduate education as the cornerstone of his career: "I realized then how grateful I was for the education I received here."

So, last year when his wife, Jean Hiivala, inherited money from a family member, she decided to make a gift to the Department her husband had graduated from. "I knew we didn't really need the money to live, we have a comfortable enough life," said Jean. "I thought, we should give it to the University of Toronto — I wanted to make sure the money went to work, making a difference."

"Initially, the intention was that we would donate $100,000," said Jean Hiivala. "But after we heard a number of options, we felt we had a special connection to each of them and decided to increase the gift to $200,000." The Hiivalas decided to direct their funds to three distinct areas within ECE. Their gift supported the creation of the *Jean & Lauri Hiivala ECE Undergraduate Award* and funded the purchase of a large advanced battery for ECE's new DC Microgrid.

But when the Hiivalas learned about a nascent research project led by Professor Piero Triverio (ECE) that would explore how computer simulations can help to identify why heart bypass grafts fail in patients with coronary artery disease, they felt compelled to support this research area too. The project was the perfect marriage between engineering and healthcare, honouring Jean's career as a nurse. This particular subject was also very close to their hearts, Lauri's in particular. "Lauri had bypass surgery in 2011, so this research project piqued our interest." said Jean. But it was only after the *Jean & Lauri Hiivala Research Fund for Heart Health* was established that the couple learned that one of the collaborators on Professor Triverio's project is Dr. Stephen Fremes — the surgeon who performed Lauri's bypass operation.

"It doesn't get much closer to our hearts than that." said Jean.

Fall Alumni Networking Lecture & Reception

Alumni of all ages returned to Skule™ to network with their classmates and to hear Professor Joyce Poon share the latest on her research in a talk titled: “Beyond Moore’s Law: Light, Brain, and Computing”.

PHOTOS BY
CAITLIN FREE PHOTOGRAPHY

Fourth-Year and Alumni Celebration

Alumni, professors and staff joined together with graduating fourth-year students at the end of their busy Design Fair week to celebrate their accomplishments and to welcome them to the ECE alumni community. Alumnus John Macdonald (ElecE 7T9) delivered an inspiring keynote address.

PHOTOS BY
CAITLIN FREE PHOTOGRAPHY

Alumni Reunion

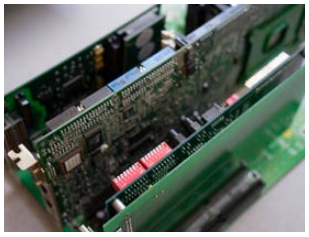
ECE alumni returned to campus for our annual lunch and lab tours. Attendees sat down for lunch with their classmates and exchanged Skule™ memories before they toured the Energy Systems Lab and heard presentations from the University of Toronto Aerospace Team (UTAT). Join us for the next Alumni Reunion on June 1, 2019!

PHOTOS BY
LAURA BROWN

Convocation

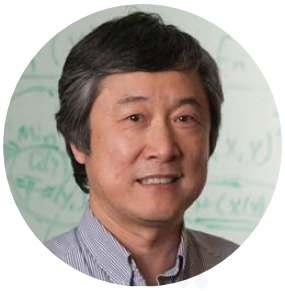
The graduating class of 1T8 and 1T7+PEY were joined by friends, family, faculty and staff at ECE's reception at Hart House where the newest group of ECE alumni were celebrated before their Convocation ceremony at Convocation Hall.

PHOTOS BY
CAITLIN FREE PHOTOGRAPHY



DISTINGUISHED LECTURES SERIES 2018 - 2019

The Edward S. Rogers Sr. Department of Electrical & Computer Engineering
UNIVERSITY OF TORONTO



Li Deng
Citadel

9 October 2018

From Modeling Speech and Language to Modeling Financial Markets

Eric Mazur
Harvard University

18 October 2018

Extreme Optics with Zero-Index

Jean Gotman
McGill University

15 November 2018

Combining EEG and fMRI: A Powerful Tool to Study Epilepsy

Vivienne Sze
Massachusetts Institute of Technology (MIT)

22 November 2018

Energy-Efficient Edge Computing for AI-driven Applications

Jeff S. Shamma
King Abdullah University of Science & Technology

14 February 2019

Distributed Protocols for Cooperative Multi-Robot Systems

Duncan Callaway
University of California Berkeley

14 March 2019

Decentralization in Energy Systems: Absorbing Solar and Storage into Grids

Ada S. Y. Poon
Stanford University

21 March 2019

Wireless Bioelectronics

Cary Yang
Santa Clara University

11 April 2019

Nanocarbon Interconnects

All lectures take place in room 1105 of the Sandford Fleming Building at 4:00 p.m.

uoft.me/dls

DIRECTORY

The Directory section contains a listing of the research projects currently underway in ECE.

DIRECTORY

The Directory section contains a listing of the research projects currently underway in ECE.

The Edward S. Rogers Sr. Department
of Electrical & Computer Engineering
UNIVERSITY OF TORONTO

ECE RESEARCH
DIRECTORY

THE EDWARD S. ROGERS SR. DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING
10 KING'S COLLEGE ROAD, TORONTO ON M5S 3G4 / PUBLICATION MAIL AGREEMENT NUMBER: 42887022

This Directory contains a listing of all research projects currently underway in ECE. Projects are listed alphabetically by principal investigator, and categorized by topic or field using eleven distinctive icons.

ARTIFICIAL INTELLIGENCE

BIOMEDICAL

COMMUNICATIONS

COMPUTERS

ENERGY & POWER

ENGINEERING/SCIENCES

INFORMATION TECHNOLOGY

ROBOTICS

SECURITY

SOFTWARE

TRANSPORTATION

AARABI, PARHAM							•				
ABDELRAHMAN, TAREK				•							
ADVE, RAVIRAJ	•	•	•				•				
AITCHISON, STEWART						•					
AMZA, CRISTIANA				•			•				
ANDERSON, JASON				•			•				
BARDAKJIAN, BERJ		•				•					
BETZ, VAUGHN	•	•		•		•	•				
BROUCKE, MIREILLE		•				•		•			
BROWN, STEPHEN				•			•				
CHAN CARUSONE, TONY	•		•	•			•				
CHENG, HAI-LING MARGARET		•				•					
CHOW, PAUL				•			•				
DAVISON, EDWARD		•			•	•					
DAWSON, FRANCIS					•						
DRAPER, STARK			•	•			•				
ELEFTHERIADES, GEORGE						•					
ENRIGHT JERGER, NATALIE				•							
FREY, BRENDAN		•	•								
GENOV, ROMAN		•	•								
GOEL, ASHVIN				•			•			•	
GULAK, GLENN			•				•				
HATZINAKOS, DIMITRIOS		•				•	•				
HELMY, AMR S.			•	•	•	•	•				
HERMAN, PETER						•					
HOOSHYAR, ALI					•						
HUM, SEAN			•			•					•
IIZUKA, KEIGO		•				•					
IRAVANI, REZA					•						
JACOBSEN, HANS-ARNO			•	•			•				
JOHNS, DAVID					•		•				
JOY, MIKE		•									
KHERANI, NAZIR		•			•	•					
KHISTI, ASHISH			•	•			•				
KSCHISCHANG, FRANK			•								
KUNDUR, DEEPA	•		•		•	•	•		•		
KWONG, RAYMOND						•			•		
LEHN, PETER					•						•
LEON-GARCIA, ALBERTO			•	•	•	•					•
LEVI, OFER		•				•					
LI, BAOCHUN				•							
LIANG, BEN	•		•	•	•		•				

LIE, DAVID				•					•		
LIEBEHERR, JORG			•								
LISCIDINI, ANTONIO			•			•	•				
LO, HOI-KWONG			•						•		
MAGGIORE, MANFREDI			•			•		•			
MANN, STEVE		•	•	•	•	•	•				
MOJAHEDI, MO				•		•					
MOSHOVOS, ANDREAS				•			•			•	
NACHMAN, ADRIAN		•				•					
NAJM, FARID				•			•				
NG, WAI TUNG					•	•	•				
PAVEL, LACRA	•					•	•				
PHANG, KHOMAN											
PLATANIOTIS, KONSTANTINOS N. (KOSTAS)		•	•	•			•				•
POON, JOYCE		•	•			•	•				
PRODIC, ALEKSANDAR					•	•					
QIAN, LI			•			•	•				
ROSE, JONATHAN	•	•		•						•	
SARGENT, EDWARD		•			•	•					
SARRIS, COSTAS			•			•	•				•
SCARDOVI, LUCA		•				•					
SHEIKHOLESLAMI, ALI	•		•	•		•	•				
SOUSA, ELVINO		•					•				
STUMM, MICHAEL				•						•	
TATE, JOSEPH (ZEB)					•						
TAYLOR, JOSHUA					•						
TRESCASES, OLIVIER					•		•				•
TRIVERIO, PIERO		•		•	•	•	•				
TRUONG, KEVIN		•		•							
VALAEE, SHAHROKH	•	•	•				•				•
VENERIS, ANDREAS				•							
VOINIGESCU, SORIN						•					
WONG, WILLY		•									
WONHAM, MURRAY						•					
YOO, PAUL		•				•					
YU, WEI			•				•				
YUAN, DING				•						•	
ZHU, JIANWEN				•						•	

Aarabi, Parham

WWW.APL.UTORONTO.CA

Internet Video, Audio and Image Processing

In the past few years, we have seen an exponential increase in the number of videos and images that have been recorded and placed on the internet. Smart mobile phones (Blackberry, iPhone, etc.) now enable seamless recording, transmission and sharing of videos in near–real time. Whereas just two decades ago there were a few video broadcasters and publishers, today there are millions, if not billions. With all this visual content, how do we find what we want? How do we categorize the content? How do we develop search engines that bring order to visual content just as text-based search engines (Google, Bing, etc.) brought order to the textual web? With videos and images, there are of course certain tags manually entered by users that define and categorize them. However, the 10–15 words that usually accompany a video or image can hardly describe the entire content and at best help to generally categorize the video or image or add a specific note regarding it. In fact, the vast amount of visual information online is untagged and inadequately described and as a result is difficult, if not impossible, to find. Finding all images and videos is but one problem. The appropriate categorization of visual content can result in more appropriate contextual advertisements (leading to better monetization of visual web/mobile sites). It can help in finding duplicate versions of the same video or image (which is useful for detecting copyright violations, among other applications). It can also help identify the important parts of a video segment or the most content-filled section of an image (which is useful for compressing videos and intelligently resizing images for mobile devices). The more information we can extract automatically from images and videos, the more we can address a range of practical problems including better search, better (and more contextual) monetization, copyright violations, video compression, and intelligent image resizing, as well as a broad range of other important applications. Although different approaches to understanding visual information have been explored in the past, one of the most promising is that of utilizing Extremely Large Datasets (ELDs). ELDs allow for greater accuracy in extracting information from images and videos, but in return require a substantially greater number of computations for each image processed. Examples of successful ELD systems include the Tiny Images image categorization system, which used a database of 80 million tiny images for image classification, or the Tiny Videos framework, which utilized a large library of videos for video classification. In both cases, the images and videos were resized to a “tiny” representation in order to minimize the rather large computational load. We aim to extend these research directions by exploring new hardware and software solutions that enable real-time image and video searching using large databases. Our goal can be described in the following two phases: (1) algorithm research and development (including finding ways to utilize ELDs for better image and video understanding and improved visual classification accuracy); and (2) hardware acceleration of the developed algorithms in order to enable accurate real-time searching of images and videos using ELDs. To summarize, using currently available images and videos that are either tagged or partially tagged, it is possible to develop highly accurate (but computationally demanding) systems that use this information for understanding and classifying vast amounts of untagged images and videos. In turn, the computational load can be addressed through FPGA-based hardware acceleration, which would enable the classification of an image or video to be performed in real time.

Abdelrahman, Tarek

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Automatic Performance Tuning for GPUs

Graphics Processing Units (GPUs) have been effectively used to accelerate many applications. These many-core processors deliver a performance an order of magnitude higher than multicore cores at a fraction of the power. However, GPUs require application developers to restructure, or optimize, their application codes to exploit the underlying GPU architecture. These optimizations are tedious to apply, may or may not benefit performance, and interact with one another in non-intuitive ways. The goal of this project is to ease this burden on programmers by developing compiler-based automatic performance tuning of GPU applications. We explore two approaches. The first attempts to correlate application code features with the effectiveness of the optimizations for a large set of training applications in order to build a machine-learning model. The compiler uses this model to decide what optimizations to apply. In a second approach, the space of possible optimizations is incrementally explored using heuristics to determine a good set of optimizations to apply. The project also builds the necessary compiler and run-time support for auto-tuning.

Directive-Based Programming and Optimizations for GPUs

This project develops high-level programming models for GPUs. More specifically, it involves the design and implementation of üCUDA, a directive-based language for GPUs. The language facilitates programming GPUs through simple directives added to the sequential code while maintaining the well-adopted CUDA/OpenCL programming models, and does so with no penalty to performance. We developed a prototype üCUDA compiler, which we have released to the public domain at www.hicuda.org. We are currently extending this infrastructure to support directive-based optimizations for OpenCL and CUDA kernels.

High-Performance FPGA Overlays

Field Programmable Gate Arrays (FPGAs) offer massively parallel resources that, if exploited by application developers, can deliver high levels of performance. However, the widespread use of FPGAs to accelerate applications is hindered by (1) their low-level programming abstraction that requires expertise in hardware design—expertise that application developers often lack; and (2) the long development cycles associated with FPGA design tools, to which software developers are not accustomed. In this project, we design, implement and evaluate overlays (FPGA circuits that are in themselves programmable) that can make the use of FPGAs by software developers easier. We designed and prototyped an overlay architecture that projects the software model of

pipelined dataflow graphs (DFGs). Instances of this overlay architecture can deliver performance in the gigaflops range that scales with FPGA resources, and are fast and easy to program. We are currently exploring compiler-based solutions for automatic extraction of DFGs of applications; determining the best overlay instance for a given application; extending the design of the overlay to multiple FPGA devices; and exploring a just-in-time compilation framework for dynamically and transparently translating binary code into overlay circuits.

Adve, Raviraj

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Application of Ultra-Wideband Radar for Estimation of Cardiopulmonary Motion in Magnetic Resonance Image–Guided Cardiac Interventions

Catheter-based interventions are an essential approach for the diagnosis and therapy of many cardiovascular diseases. X-ray fluoroscopic imaging is the main modality used for guiding catheterization procedures; however, this modality only provides low-contrast 2-dimensional (2D) projection images. MRI-guided catheterization requires the real-time tracking and visualization of the catheter tip with respect to high-resolution pre-procedural roadmap images for guidance. While rapid real-time 2D MR images can be obtained, they are of lower quality and the 3D roadmap images are needed to guide the catheter. However, these 3D roadmaps are static and cannot be updated in real time. This effort focuses on using an ultra-wideband (UWB) radar to monitor the heart motion during MRI-guided surgeries. The key challenge is to detect and track the heart muscle with a resolution adequate for surgeries.

Cognitive Radar: Theory and Architecture Development

Modern multifunction radar systems must execute many tasks of various levels of priority and parameters (such as execution length, possible start time, etc.). Unfortunately, the optimal sequencing of tasks is NP-hard eliminating real-time optimization as a viable option. The current approach has been to use heuristics such as executing the tasks with the earliest deadline. These heuristics are very far from optimal. In this effort, we have developed — and continue to develop — machine learning techniques that allow for real-time optimization. We have developed a Monte-Carlo tree search approach to task scheduling that requires about 1/100th the time of the optimal approach with negligible performance loss. We are currently exploring reinforcement learning approaches to task scheduling.

Design of Massive Distributed Antenna Systems in 5G Networks

Focusing on 5G networks, this effort focuses on massive distributed antenna systems (DAS) or distributed massive MIMO (DM-MIMO) systems. The term “distributed antenna, systems” refers to a group of geographically distributed remote radio heads (RRHs), each with a single antenna or just a few antennas, coordinating transmissions to groups of users. The key benefit of DAS is the relative uniformity in coverage (as antennas are distributed across the coverage area) and increased robustness against fading including, importantly, shadowing (since users are able to connect to multiple, spatially distributed, RRHs simultaneously). However, greatly expanding the number of RRHs raises enormous challenges in both theoretical analyses and practical designs. Topics of specific interest are optimizing the location of RRHs, incorporating backhaul into the analysis and enabling user-centric connections.

Low-Cost, Application-Aware, High-Fidelity Methods for 5G Systems and Beyond

5G networks will differentiate themselves from the current 4G by their increasing heterogeneity: heterogeneity in demands (a wider variety of applications), heterogeneity in access (multilayer access networks or heterogeneous networks), heterogeneity in infrastructure (low-cost access points to complicated, massive multiple-input, multiple-output, or MIMO, base stations). This project focuses on how to address this growing heterogeneity in a cohesive, practical manner to optimize the limited spectrum and power resources available. We develop algorithms in a user–application aware manner. Of specific interest are metrics of growing importance such as the latency encountered by data streams.

Aitchison, Stewart

PHOTONICS.LIGHT.UTORONTO.CA/AITCHISON

Nanophotonics for Optical Signal Processing and Sensing

Our research falls within three areas: (1) electron beam lithography and process development; (2) photonic wires for wavelength conversion applications; and (3) photonic wires for optical sensing applications. In 2009, we officially opened our new electron beam lithography system, which allows features down to 10 nm to define across large areas. The high beam current and low stitching errors possible with this tool allow a wide range of structures to be patterned, including nanostructured surfaces for biology, sensing and photonics. Optical frequency conversion, based on second- or third-order nonlinearities, provides a mechanism for generating new wavelengths and has applications in telecommunications for agile channel allocation in a wavelength division multiplexed system and for the generation of mid-IR wavelengths for optical sensing. The use of high-refractive-index-contrast waveguides to implement wavelength conversion has many advantages. The small core size increases the local intensity, the waveguide structure can be used to dispersion engineer the waveguide to enable phase matching and resonators can be used to further enhance the conversion efficiency. Under this theme we will use the almost ideal nonlinear properties of the III-V semiconductor AlGaAs to develop efficient wavelength conversion devices based on second-order nonlinearities (difference frequency generation) and third-order effects (four-wave mixing). The ability to engineer the dispersion and field profile in a nanowire waveguide has applications in optical sensing. By narrowing the waveguide and incorporating a photonic crystal or defect state, it is possible to control the overlap of the optical field with the sensing material. Typically sensing can be done through a change in refractive index, or absorption of an intermediate

material which is sensitive to the substance to be measured, for example, platinum for hydrogen detection. Using this approach it is possible to develop a single chip with multiple sensors that could detect multiple gases, temperature, humidity and pressure.

Amza, Cristiana

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Automated Self-Management in Cloud Environments

The economy has been transformed by the delivery of web services over the Internet in the past three decades. Behind the scenes of web-based service delivery technologies are large-scale, complex information systems. These information systems consist of thousands of servers, which store client data in a consistent and persistent manner and are multiplexed among several applications. Many aspects of content delivery still currently depend on manual fine-tuning and troubleshooting by humans. As a result, the service provider is strapped, with huge human administrator costs for performance debugging, resource allocation to applications and infrastructure configuration adjustments. This is a major impediment to the efficiency of this industry, limiting reinvestment, research and development. To address this problem, we investigate innovative self-diagnosis and adaptive reconfiguration techniques for scalable and available information systems. We have designed and developed novel online performance modelling and anomaly detection algorithms and tools that form the basis for self-configuring, self-tuning and self-healing servers. We use these techniques in our data centre laboratory towards automatically providing quality of service for a range of dynamic content services such as e-commerce, online bidding and massively multiplayer games.

System Support for Parallel and Distributed Software Transactional Memory

Because of the increase in complexity and ubiquity of large-scale parallel and distributed hardware environments, simpler parallel programming paradigms become key. Transactional Memory (TM) is an emerging parallel programming paradigm for generic applications that promises to facilitate more efficient, programmer-friendly use of the plentiful parallelism available in chip multiprocessors and on cluster farms. We developed and optimized libTM, a Transactional Memory library that can be used in connection with C or C++ programs. libTM implements Transactional Memory for generic applications, and it allows transactions on different processors (or machines) to manipulate shared in-memory data structures concurrently in an atomic and serializable (i.e., correct) manner. There is no need for the application to do explicit fine-grained locking by acquiring and releasing specific locks on data items. Instead, a cluster-based run-time system automatically detects data races and ensures correct parallel execution for generic parallel programs. Any detected incorrect execution resulting from a data race is rolled back and restarted. In this project we have focused on reducing the software overhead of run-time memory access tracking and consistency maintenance for Transactional Memory support. We currently support applications with highly dynamic access patterns, such as massively multiplayer games. We have shown that Transactional Memory not only simplifies the programming of these applications, but can also improve performance and scaling relative to that obtained by using traditional locking techniques for code parallelization for the same application.

Anderson, Jason

JANDERS.EECG.TORONTO.EDU

Circuit and Architecture Techniques to Improve FPGA Speed, Power, Area and Ease of Use

Field-programmable gate arrays (FPGAs) are computer chips that can be programmed by the end user to implement any digital circuit. FPGAs can be thought of as “configurable” computer hardware, making them an ideal platform to realize application-specific hardware accelerators that are used in tandem with standard processors to improve computational throughput and energy efficiency. However, as programmable chips, FPGAs naturally consume more power, are slower, and use more area than fixed-function chips. In this research thrust, we are undertaking several circuits/architecture-related projects to improve FPGA speed, area, power and ease of use, particularly for specific application domains, such as machine learning.

Coarse-Grained Reconfigurable Architectures

Coarse-grained reconfigurable arrays (CGRAs) are a style of programmable logic device situated between FPGAs and custom ASICs on the spectrum of programmability, performance, power and cost. CGRAs contain large coarse-grained blocks and datapath interconnect, possessing less flexibility than FPGAs. The reduced flexibility implies less overhead for programmability and better performance, power and cost than FPGAs for certain applications, namely those applications for which the computational and communication patterns are well aligned with the underlying CGRA capabilities. CGRAs have been proposed by both academia and industry; however, prior works have mainly been “point solutions” without broad architectural exploration or comparisons with competing CGRAs. In this project, we are researching CGRA architectures, and in particular, are developing a software modelling and, simulation framework, CGRA-ME, that will enable the scientific exploration and evaluation of a wide range of CGRA architectures.

LEGUP.EECG.TORONTO.EDU

High-Level Synthesis of Hardware Circuits from Software Programs

High-level synthesis (HLS) raises the abstraction level for hardware design by allowing a software program to be automatically synthesized into a hardware circuit. HLS aims to offer the flexibility and ease of use associated with software, along with the speed and energy advantages of customized hardware. Both of the major FPGA vendors have been investing heavily in HLS in recent years, and there has been much research on the topic in academia as well. State-of-the-art HLS is nearing the

point where software engineers are able to design hardware, with the quality of the HLS hardware produced being comparable to human-crafted implementations. LegUp is a high-level synthesis tool under active development at the University of Toronto. LegUp accepts a C program as input and automatically compiles the program to a hybrid architecture comprising a processor (a soft-core MIPS or a hardened ARM) and custom hardware accelerators. Results show that LegUp produces hardware solutions of quality comparable to that of commercial high-level synthesis tools. LegUp is open source and freely downloadable (legup.eecg.toronto.edu), providing a powerful platform that can be leveraged for new research on a wide range of HLS and hardware/software co-design topics.

Bardakjian, Berj

HEART.IBME.UTORONTO.CA/~BERJ/BERJ.HTML

Computer Models of Electrical Rhythms of the Brain

Meso- and micro-level computer models of the electrical rhythmic activities of the brain are developed to (1) elucidate the biophysical basis of cross-frequency coupling in the electrical activities in the neuroglial networks of the brain, and (2) provide platforms for testing neuromodulation strategies for dealing with disorders associated with brain pathologies (in particular epilepsy). Meso-level models consist of coupled nonlinear oscillators based on cognitive rhythm generation dynamics (as developed by our team), whereas micro-level models consist of cellular models based on Hodgkin-Huxley dynamics.

Neuroengineering of the Brain

The main themes of the research fall within the general field of neural engineering and, in particular, the electrical rhythmic activities of the brain. The purpose is to (1) characterize both normal and pathological brain states and (2) anticipate, detect and then abolish, pathological brain states, such as epileptic seizures. The approach is to characterize the spatiotemporal relations of the electrical rhythmic activities in neuronal populations and use cognitive rhythm generators as adaptive devices to classify and mimic the dynamical features of the biological neural networks in the brain. Implantable neuromimetic cognitive devices will be developed as low-power hardware incorporated into the biological neural networks in a closed feedback loop. These will provide implantable devices to be used as therapeutic tools for brain disorders. Another focus is the analysis of scalp EEG for (1) epileptogenic source localization using cross-frequency coupling features of the brain's electrical rhythms, and (2) prediction and detection of epileptic seizures using machine learning.

Betz, Vaughn

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Deep Learning Hardware Acceleration

Deep learning has led to breakthrough accuracy in many fields, from image recognition, through automatic translation and recommendation systems. However, the high accuracy of deep learning comes with a high computational and power cost, which makes it more difficult and expensive to deploy in embedded system that are becoming increasingly ubiquitous. In this project we seek to make efficient programmable hardware accelerators for deep learning using current FPGAs, and, more fundamentally, seek to improve the architectures of these programmable chips to make them more effective accelerators for deep learning. At the same time, we will preserve the programmability of FPGAs that makes them suitable for a wide variety of applications and deep learning systems.

Improved FPGA Architecture and CAD

My team seeks to find both better architectures and better Computer-Aided Design (CAD) tools for a type of integrated circuit—Field-Programmable Gate Arrays (FPGAs). FPGAs are a type of computer chip that can be reprogrammed to perform any function. As the cost of creating chips with billions of transistors has risen to $100 million, most applications cannot justify a custom-fabricated chip and instead are best served by a reprogrammable chip. Our research seeks to find the best "architectures" for FPGAs—what function blocks should they include and, perhaps even more important, how can we best programmably interconnect the huge number of function blocks in modern FPGAs? We are investigating how the circuitry of FPGA programmable interconnect should be modified to take best advantage of the latest (22 nm and below) process technologies. We are simultaneously investigating a radical change to FPGA on-chip communication in which we augment conventional FPGA programmable interconnects with packet-switched networks on chip. This fundamentally raises the level of abstraction of communication on the chip, but requires new CAD tools, which we are also developing, to automate this new and different design flow. We are also making FPGAs more power-efficient by finding ways to run them at lower voltages. We also seek to find new algorithms and computer-aided design tools to allow FPGA designs to be completed more quickly and to run at higher speeds and make more efficient use of the chip. In particular, we are looking at how to make highly scalable placement and routing algorithms that can handle the latest chips, which contain billions of transistors, in a reasonable run time.

Simulation and Optimization of Photodynamic Cancer Therapy

We are seeking to make a new form of light-activated cancer treatment, photodynamic therapy or PDT, more effective by simulating the outcome of this treatment for a range of possible light-source placements and types, and by automatically suggesting optimized locations for the light sources. This requires advanced computation in which we simulate the paths of millions of photons in complex human tissue to determine an accurate assessment of where light will be absorbed and hence where tissue will be destroyed. By combining our fast, hardware-accelerated light physics simulator with advanced optimization algorithms we seek to determine the best arrangement of fibre-optic light sources to destroy a tumour (and minimize the exposure of healthy tissue) by activating a photosensitive catalyst only in a local area of the patient's body.

Broucke, Mireille

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Control for Complex Specifications

The field of Systems Control has traditionally been focused on steady-state control specifications in the form of stabilization and tracking. The goal of the project is to develop a theory of control for complex specifications, in particular enabling systematic methods of design and control of the transient phase of a dynamic system. These complex specifications may include safety and liveness specifications, logic-based specifications and temporal specifications. Problems of control with complex specifications arise in all of the disciplines that apply Systems Control, ranging from robotics to process control.

Model of the Human Cerebellum

The aim of this project is to develop a mathematical model of the human cerebellum, the part of the brain responsible for motor control. A complete understanding of the cerebellum is one of the great open problems of neurobiology today. As a first step, we focus on experimental findings from cognitive psychology regarding a visuomotor experiment in which a human subject makes repeated fast reaches to a target in the presence of an unknown visual disturbance. This experiment has been investigated in psychology for at least 20 years. Our methodology contrasts with all other approaches taken by psychologists today. Rather than deriving a model based on analysis of experimental data, we first formulate the fast-reach problem as a mathematical problem of control theory. Then we synthesize a solution using control design methods. Finally, we use our synthesized solution as the starting point to fit to the observed data of the experiment. Using eight different qualitative behaviours, we argue that we have the correct model of the experiment. We believe this model is a breakthrough in the understanding of the cerebellum. As a final and significant step we will investigate the underlying neurobiology that gives rise to our derived mathematical model.

Patterned Linear Systems

Complex dynamic systems that are made of a large number of simple subsystems with simple patterns of interaction arise frequently in natural and engineering systems. There is generally no overarching theory that explains the phenomena exhibited by such systems. We have introduced a class of linear control systems called patterned systems, which mathematically capture the structure of a collection of identical subsystems with a fixed pattern of interaction between subsystems. The project involves developing a control theory for patterned systems and our approach is based on the geometric theory of linear control systems. The aim of our study is to determine if patterned systems may provide a template for the development of a more unified framework for dealing with systems, typically distributed, which consist of subsystems interacting via a fixed pattern.

Brown, Stephen

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Computer Acceleration Using FPGAs

My research is focused on many different aspects of field-programmable gate array technology, including the design of the chip architectures and the algorithms that are used to implement circuits in these devices, as well as applications of FPGAs. In addition to my faculty position at the University of Toronto, I maintain an active involvement in the Intel Programmable Solutions Group (formerly Altera Toronto Technology Centre), where I provide direction for the University Program for Intel FPGAs. By combining my involvement in both the University of Toronto and Intel, it has been possible to develop research results that are both interesting from the academic point of view and of practical use when implemented in an industrial-quality CAD tool. My current research effort is in the area of CAD flows for FPGA devices and specifically in the development of new methods of efficiently compiling high-level language code (such as C code) into circuits that can be implemented in FPGA devices.

Chan Carusone, Tony

ISL.UTORONTO.CA

Circuits and Systems for Broadband and Spectrally-Efficient Communication

This project will explore circuits and systems to reduce the cost and power consumption of new and emerging spectrally-efficient broadband communication, including 5G technologies. Low-cost flexible transceivers achieving low power consumption are sought. Circuits and systems amenable to implementation in CMOS will permit their integration alongside other digital signal processing, further reducing power and cost. Prototyping the circuits and systems in advanced (28-nm and below) nanoscale CMOS provides unique training for graduate students, while also enhancing the work's commercial relevance and impact.

Highly Integrated Optical Transceivers

Optical fibre is already the dominant communication medium for high data rates over long distances. However, there is increasing interest in the use of optical fibre for communication over much shorter distances. For example, in rack-mounted computing and storage environments, where the cost of operating the equipment over its lifetime now exceeds its initial purchase cost, optical communication becomes increasingly attractive at data rates above 50 Gb/s. At these data rates, the losses inherent in communication over copper cables cause it to consume more power than optical communication, impacting energy costs. Optical fibre's thin diameter permits better airflow (hence, reduced cooling costs) and easier maintenance than copper cables. Fibre's immunity to electromagnetic interference is attractive for automotive and other harsh environments. Moreover, optical fibres can be routed in tight bundles with much less crosstalk than copper wires, making it a scalable medium. Even in consumer applications demanding multi-Gb/s throughput, optical cables are attracting increasing interest because of their light weight, flexibility and

thin diameter. To exploit the fundamental advantages of optical communication in these areas, we develop highly integrated, dense and low-power optical transceiver circuits. We prototype our developments in the most advanced integrated circuit technologies available.

Intelligent Sensing Hardware

We are developing microelectronics for intelligent sensing applications. Specifically, we are interested in fully customized and dedicated architectures and circuits that provide low cost and power consumption and significant acceleration for a wide variety of applications such as 3D imaging, object and speech recognition. We are developing and testing prototype integrated circuit demonstrations in advanced CMOS technologies.

Next-Generation Chip-to-Chip Interfaces

This project is exploring circuits and systems to reduce the cost and power consumption of digital interfaces between chips inside of our networking and computing infrastructure equipment. These interfaces are increasingly the bottleneck in overall system performance. Targeting serial data rates above 100 Gb/s, this project combines research on application-specific signal processing and high-speed analog circuit design. Prototype interfaces are being developed in nanoscale (below 20 nm) CMOS technologies to permit their integration within the digital processors that drive infrastructure networking and computing. Close collaboration with industry provides unique opportunities for impact and training.

Cheng, Hai-Ling Margaret

CHENG.IBBME.UTORONTO.CA

3D Bioprinting the Mammalian Heart

The goal of this project is to build a mammalian heart using principles of developmental biology and tissue engineering.

Early Detection of Fibrosis

Fibrosis, or scarring, is a pathological process that occurs in many life-threatening diseases, such as heart failure, kidney failure, and liver disease. To date, there is no specific diagnostic tool that is capable of detecting fibrosis, especially in the early stages when organ function has not deteriorated and is still amenable to treatments that halt progression. Our program in fibrosis imaging seeks to develop a magnetic resonance imaging platform that allows direct detection of fibrosis even at the early stage of scar development. The end goal is to enable early detection in the various organs in the body susceptible to fibrosis.

Magnetic Resonance Imaging of Microvascular Dysfunction

The microvasculature, or the nutritive blood vessels in our body, is essential to maintaining tissue health. Loss of proper microvascular function underlies a broad spectrum of conditions, including neurological disease, diabetes, and cardiovascular disease. This is why being able to evaluate the health of these small blood vessels is important for early diagnosis and assessment of treatment effect. Yet, despite the ability of current advanced technologies to probe microvascular function, such as blood flow, in a non-invasive manner, it remains very difficult to detect the early signs of microvessel dysfunction. In this research program, we are developing new non-invasive imaging methods based on magnetic resonance imaging to find those early changes sooner than we can today, in the hope that early detection will enable early intervention for improved outcome.

Magnetic Resonance Imaging for Tissue Engineering

This broad research program aims to advance the capabilities of non-invasive magnetic resonance imaging (MRI) for enabling critical advances in tissue engineering and regenerative medicine. Work focuses specifically on MRI on a physiological, cellular and molecular level to tackle difficult tissue-engineering problems such as angiogenesis, scaffold-based and cell-based therapy.

Non-invasive Monitoring of Stem Cell Therapy by Magnetic Resonance Imaging

The ability to see cells inside a living body can transform how we detect and diagnose disease and monitor treatment. From differentiating healthy from unhealthy cells, to tracking therapeutic cells that are injected into the body, cellular imaging is an active biomedical research area. Yet, when we think of cellular imaging, we usually think of looking at samples under a microscope. This research program strives to develop a similar capability to look at cells using magnetic resonance imaging (MRI), for non-invasive, deep-tissue penetration in a living subject. Our goal is to improve detection sensitivity and specificity so as to make MRI the technology of choice for non-invasive human cellular imaging.

Chow, Paul

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FPGAs for Cloud Computing Platforms – Virtualization and Applications

Field-Programmable Gate Arrays (FPGAs) are a programmable hardware resource that can be used to build application-specific hardware computing elements for many types of computation and network processing. In a cloud-based platform, the hardware of the computing resources is abstracted from the user in the form of a virtual machine that looks uniform regardless of the physical hardware platform. This project explores (1) how to place FPGAs into this virtualized environment when using Open Stack; and (2) how to scale up heterogeneous programming environments to work in a large-scale heterogeneous environment. The prototyping platform is the SAVI Networks platform (savinetwork.ca) where real applications are being built to drive the development of the programming environment as well as to characterize the behaviour and performance of large-scale systems.

Internet-Scale Memory Systems

With the vast amount of data accessed and stored using the Internet, new memory architectures are required to host the data that can provide low latency access, low power dissipation and a compact form factor. Current systems use the collected main memory of a cluster of high-end servers for an application that does not need the computation power of such systems. This project explores the intrinsic requirements of such systems without the constraint of using common compute server platforms. Field-Programmable Gate Arrays will be used to develop more flexible, application-specific and novel architectures for building Internet-scale "big data" memory systems.

Programming Models and Architectures for Large-Scale Reconfigurable Computing Systems

This research investigates approaches to computing using systems of multiple, heterogeneous computing devices. The heterogeneity addresses the need for special-purpose computing architectures that provide performance or other efficiencies, such as more efficient energy usage. A key focus is the use of Field-Programmable Gate Arrays (FPGAs), a form of configurable hardware. Such systems can be found in an embedded device or in high-performance computing systems. Important issues being addressed are better methods for programming, testing and debugging, and system architectures. Much of the research is driven by applications. One aspect is to work with users of high-performance computing facilities and help them to improve performance through better algorithms and the use of accelerators implemented with FPGAs and/or GPUs.

Davison, Edward

WWW.CONTROL.UTORONTO.CA/PEOPLE/PROFS/TED

Control of Large-Scale Decentralized Systems

Our research is focused on the control of large-scale systems, where only limited information about the overall system is available to the control agents of the system. Such systems occur often in modern industrial society, for example, in chemical engineering, electrical power systems, aerospace systems, transportation systems, building temperature control systems, large flexible space structures and pulp and paper control systems, as well as in other areas such as management science and biological systems. Problems that immediately arise from large-scale systems are current areas of research: decentralized control, intelligent control, fault-tolerant control and the control of unknown systems. A direct application of this research is presently being used in the control of large flexible space structures, earthquake-resistive building structures, and electrical power systems, with particular focus on microgrid systems and spinal cord injury patients.

Dawson, Francis

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Improving Energy Efficiency of Energy Conversion Processes

General research interests are in the area of modelling systems powered by electrical energy. At the component level, the current focus is on developing improved models that can describe the electric and thermal fields in electrochemical storage devices. The objective is to use reduced order multiphysics models to develop energy management controllers that can extend the life of an energy storage device. At the system level, the objective is to determine the system architecture and control philosophy that lead to an optimal integration of energy storage devices and power converters, subject to a specific generating and electrical load profile. Other areas of interest include the modelling of thermoelectric, piezoelectric and plasma devices in conjunction with the electrical source.

Draper, Stark

WWW.ECE.UTORONTO.CA/PEOPLE/DRAPER-S

Anytime Updating in Synchronized Stochastic Gradient Descent for Machine Learning

In modern deep neural network training problems the scale of data has outpaced the memory and processing capabilities of individual computers. For example, applications in image recognition can require ExaFLOPs of computation and petabytes of data. Many deep neural network training problems are solved using the stochastic gradient descent (SGD) algorithm. However, in these large-scale training problems, performing SGD in a single processor can be infeasible due to limited storage and computation power or to high wall-clock time. These facts together with the advent of high performance computing, GPU-accelerators, and computer clusters, have driven the development of parallelized variants of SGD. Synchronous SGD is one method to perform SGD in parallel. In Synchronous SGD, workers in parallel all receive the latest parameter vector, compute their gradients, and send their updates to the master node to be combined. Synchronous SGD waits for all the parallel workers to finish the updates. Therefore, the time to update depends on the slowest worker. These slow workers, referred to as stragglers, can introduce significant delays in obtaining the final output. In general, stragglers cannot be completely removed from a distributed computation system. In this project, we exploit stragglers (of course, along with non-stragglers) rather than avoiding them. The central idea is to give all workers a fixed amount of time to work in each computational epoch. As such, the waiting time of the master node is deterministic (except for possible communication delays) and is no longer limited by variability in finishing times. Furthermore, we use the outputs of all workers, both fast and slow. Our method effectively introduces data redundancy to enhance robustness, but at the same time it uses that redundancy to effect faster convergence rather than producing wasteful (unused) computation. We perform extensive numerical evaluations in the Amazon EC2 cloud.

Distributed Coding of Multispectral Images

The acquisition and compression of multispectral images is often performed in an environment where resources such as computational power and memory are scarce. To that end, we propose a new extremely low-complexity encoding approach for compression of multispectral images, shifting the complexity to the decoding. Our method combines principles from compressed sensing and distributed source coding. Specifically, the encoder compressively measures blocks of the band of interest and uses syndrome coding to encode the bitplanes of the measurements. The decoder has access to side information, which is used to predict the bitplanes and decode them. The side information is also used to guide the reconstruction of the image from the decoded measurements. Our experimental results demonstrate significant improvement in the rate–distortion trade-off when compared to similar low-complexity coding schemes.

Feature Transform Based Semi-supervised Learning

In this project, we develop a semi-supervised learning (SSL) approach based on feature transformation and the boundary tree algorithm. The recently proposed boundary tree algorithm allows efficient nearest-neighbour classification on labelled data. In general, nearest-neighbour methods work best when input data clusters are well separated and possess a simpler topology. However, most real-world datasets do not have these favourable qualities; therefore, they give an inferior performance when tested against nearest-neighbour methods such as the boundary tree algorithm. The recently proposed differentiable boundary tree algorithm makes use of a neural network to transform real-world data into a simpler intermediate representation that works well on the boundary tree classifier. This joint classifier has proven to produce better results than individual classifiers in terms of accuracy and representability of original data. In our project, we extend this idea of differentiable boundary trees to the SSL paradigm where a large amount of unlabelled data is available with a small number of labelled data. We reformulate the original problem to leverage unlabelled data to train a joint classifier. Performance testing is done on the standard MNIST handwritten image dataset.

Hardware-Aware Motion Estimation via Low-Resolution Motion Hints

Developments in video coding standards such as HEVC, and the earlier development of H.264/AVC, focused on the compression of camera-captured video sequences. However, screen content coding (SCC) has rapidly emerged as an extension in today's video coding standards to enable compression targeted towards videos containing substantial amount of still or moving rendered graphics, text, and animation. Screen content typically exhibits a high number of identical blocks, large regions containing uniform motion, and no sensor noise. These properties, if properly leveraged, can provide significant performance improvements for SCC. On the other hand, power management, latency, and portability are high-priority design considerations when it comes to the characteristics of the devices to display screen content. We first propose a methodology for hardware-constrained video coding by taking advantage of the freedom given to designers to alter encoder input data at the encoder. We design an algorithm that exploits the characteristics of screen content to improve compression performance while prioritizing hardware design constraints. The algorithm determines a set of motion hints that are passed to the hardware-constrained encoder as side information to aid in the video coding process. We develop an application-specific implementation of this design in partnership with Advanced Micro Devices (AMD), customized to AMD's video encoding operations. The implementation shows that our proposed methodology and algorithms effect significant improvement for SCC under hardware constraints and can come within 1.5 dB of pure software video codec compression. The work with AMD is supported by NSERC.

Large-Scale Linear Programming Decoding via the Alternative Direction Method of Multipliers

When binary linear error-correcting codes are used over symmetric channels, a relaxed version of the maximum likelihood decoding problem can be stated as a linear program (LP). This LP decoder can be used to decode at bit error rates comparable to state-of-the-art belief propagation (BP) decoders, but with significantly stronger theoretical guarantees. However, LP decoding when implemented with standard LP solvers does not easily scale to the block lengths of modern error-correcting codes. In this project we draw on decomposition methods from optimization theory, specifically the Alternating Direction Method of Multipliers (ADMM), to develop efficient distributed algorithms for LP decoding. The key enabling technical result is a nearly linear-time algorithm for two-norm projection onto the parity polytope. This allows us to use LP decoding, with all its theoretical guarantees, to decode large-scale error-correcting codes efficiently. Our approach has the potential to solve longstanding issues of great industrial importance such as the "error-floor" problem of low low-density parity-check (LDPC) codes, the existence of which has slowed the adoption of these state-of-the art codes for applications requiring ultra-low error rates, such as magnetic storage. In addition to continued development of theoretical results, we have recently shown that the algorithms are compatible with hardware. We have completed a full-scale implementation in a field-programmable gate array (FPGA). This hardware implementation produced a number of interesting innovations needed to synthesize efficiently in hardware the computational primitives of ADMM-LP decoding.

Eleftheriades, George

WWW.WAVES.UTORONTO.CA/PROF/GELEFTH/MAIN.HTML

Engineered Materials (Metamaterials) and Surfaces (Metasurfaces) from Microwave to Optical Frequencies

We are developing paradigm-shift metamaterial devices and subsystems, and related technologies from RF/microwaves to optical frequencies. Metamaterials are engineered materials with unusual electromagnetic properties. Such properties include negative refraction, enhanced evanescent waves through resonant amplification and sometimes a negative group velocity. Our vision is to develop metamaterials that can manipulate and control electromagnetic waves, much

as conducting wires manipulate the flow of electrons. Both three-dimensional volumetric and surfaces (metasurfaces) metamaterials are being developed. A recent effort concerns the development of ultrathin metasurfaces for wavefront manipulation, such as refraction (bending of incident plane waves or Gaussian beams), lensing and controlled antenna beam formation. Application areas include super-resolution microwave and optical microscopy, detection and sensing, advanced hardware for wireless communications, wireless power transfer, reduction of interference, space technology, satellite communications, radar, defence, solar-cell concentrators, thermophotovoltaics, infrared focal-plane arrays and many more. Examples of devices include small antennas, low-cost steerable antenna arrays, multifunctional RF/microwave components (including active devices), sub-diffraction imaging lenses and probes (even operating in the far field), ultrathin lenses, invisibility cloaks and related "transformation optics" lenses, plasmonic optical circuits, plasmonic waveguides and nano antennas. Research includes both experimental work and fundamental theory. Our research is supported by several industrial partners, government agencies and laboratories. Graduates from our group have been quite successful in securing faculty positions in academia (e.g., UMich, UAlberta, McGill, U of T and UBC) and industry (e.g., Apple, AMD, Google, Blackberry, Freescale, Space X and Motorola).

Enright Jerger, Natalie

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Approximation Computing

Approximate computing explores opportunities that emerge when applications can tolerate error or inexactness. These applications, which range from multimedia processing to machine learning, operate on inherently noisy and imprecise data. As a result, we can trade off some loss in output value integrity for improved processor performance and energy efficiency. Memory accesses are costly both in terms of latency and energy. We are exploring microarchitectural techniques that leverage approximation to reduce the cost of data storage and data communication. For example, we explore load value approximation, a novel microarchitectural technique, to learn value patterns and generate approximations of the data. The processor can use these approximate data values to continue executing without incurring the high cost of accessing memory, removing load instructions from the critical path. Load value approximation can also be used to inhibit approximated loads from accessing memory, resulting in energy savings. We have also proposed two novel cache architectures to reduce redundant data through approximation. Moving forward, we are focusing specifically on applying approximate computing to machine learning applications that can be made robust to errors. We are also focusing on specific opportunities to leverage approximate computing to design more energy-efficient processors for energy-harvesting internet of things (IoT) devices.

Architectures for Energy-Harvesting IoT Devices

This project combines research in approximate computing, power-efficient design and machine learning. We are broadly interested in designing next-generation energy-harvesting IoT (Internet of Things) devices with a focus on architectural enhancements to allow efficient computation given limited and unpredictable power budgets and applications such as machine learning, which will become prevalent in edge devices. These devices are characterized by intermittent computation – that is, computation that must be stopped and restarted in power outages, which can occur frequently. To better understand this design space, we have developed an analytical model that allows designers to quickly reason about a variety of trade-offs in the design of processors and software systems for energy harvesting. Moving forward, we are developing a simulation infrastructure that specifically targets energy-harvesting devices. This simulator will enable us to explore the idea of approximate computing in this context as well as open up new and exciting areas of architectural research.

Interconnect Solutions for Interposer-Based Systems

Silicon interposer technology ("2.5D" stacking) enables the integration of multiple memory stacks with a processor chip (and heterogeneous IP blocks), thereby greatly increasing in-package memory capacity while largely avoiding the thermal challenges of 3D stacking DRAM on the processor. Systems employing interposers for memory integration use the interposer to provide point-to-point interconnects between chips. However, these interconnects only utilize a fraction of the interposer's overall routing capacity, and in this work we explore how to take advantage of this otherwise unused resource. We are exploring approaches to extending the architecture of a network-on-chip (NoC) to better exploit the additional routing resources of the silicon interposer and to take advantage of new opportunities afforded by the interposer. We propose an asymmetric organization that distributes the NoC across both a multicore chip and the interposer, where each sub-network is different from the other in terms of the traffic types, topologies, the use or non-use of concentration, direct vs. indirect network organizations, and other network attributes. Through experimental evaluation, we show that exploiting the otherwise under-utilized routing resources of the interposer can lead to significantly better performance. Another key to enabling composable interposer-based systems is the routing algorithm that connects the individual networks-on-chip for each chip and the interposer. Designing a deadlock free global routing algorithm in this context is an open and unexplored challenge.

Simulation Methodologies for On-Chip Networks

On-die communication fabrics represent a critically important aspect in the design of future many-core computer systems. As systems scale to increasingly large numbers of on-die agents, the on-die communication fabric will factor dramatically into both the performance and the power consumption of future architectures. This research focuses on two challenges in the design of on-die communication fabrics: physically aware performance and area optimization for communication fabrics and uncore, interconnect and system power management. Within these topics, we are specifically exploring solutions to integrate cache coherence protocol traffic analysis into the early-stage on-chip network design space exploration and protocol-level information into the quality of service and DVFS mechanisms of the on-chip network. These two thrusts will

span issues of correctness, energy/performance efficiency and scalability. Current techniques to simulate on-chip networks are either time-consuming or lack accuracy in the resulting performance and power estimates. Our new traffic models will accelerate on-chip network and memory system simulation and allow researchers to reach stronger conclusions about system performance at an early design stage. These models accurately capture sharing behaviour and the interaction of dependent messages in the coherence protocol. These models are parameterized to allow a wide diversity of systems to be simulated with rapid turn-around times.

Frey, Brendan

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Algorithms for Inference and Machine Learning

Dr. Frey's group develops new inference theories that can be used for probabilistic and statistical inference in large-scale systems, such as those that arise in telecommunications, robotics, genetics, genomics, vision and signal processing. Dr. Frey is co-author of an article that introduced the factor graph and associated sum-product and max-product algorithms (IEEE Trans Info Theory 2001). A factor graph is a method for decomposing high-order probability models into simpler terms, so that the sum-product or max-product algorithm can be used to efficiently perform inference. A search for "factor graph" on Google returns over 40,000 hits. Other methods developed by Dr. Frey and his colleagues include variational methods for inference in large-scale nonlinear Gaussian models (Neural Comp 1999), the "wake-sleep" algorithm for unsupervised learning (Science 1995), cumulative distribution networks (NIPS, UAI 2008) and loopy belief propagation algorithms for low-level vision (CVPR 2000), phase-unwrapping of medical and satellite images (NIPS 2001), exemplar-based clustering (Science 2007) and facility location (AISTATS 2010).

Data Analysis and the Affinity Propagation Algorithm

Summarizing data by identifying a subset of representative examples is important for scientific data analysis and in engineered systems. Such exemplars can be found by randomly choosing an initial subset of data points and then iteratively refining it, but this only works well if that initial choice is close to a good solution. Dr. Frey's group developed a new method called affinity propagation, which takes as input measures of similarity between pairs of data points. Real-valued messages are exchanged between data points until a high-quality set of exemplars and corresponding clusters gradually emerges (Frey and Dueck, Science 2007). Because of its simplicity, general applicability and performance, the affinity propagation algorithm is widely used in science and engineering. In the past year, an online web tool developed by Dr. Frey's group was accessed over 100,000 times by over 3,000 users (unique IP addresses), 600 of which were from Canada. Google returns over 10,000 hits for the search term 'affinity propagation'. Dr. Frey's method has been applied to solve problems in biology, genetics, genomics, medicine, physics, chemistry, telecommunications, electronics, archeology, economics and social networks.

WWW.GENES.TORONTO.EDU

Deciphering the Human Genetic Code

Despite widespread claims that the human genome has provided a "book of life," it turns out that it is very difficult to understand how genes stored in the genome encode the actual genetic messages that control the life, death and ongoing activities of the cells comprising all human tissues. In the words of the famous genomics researcher Eric Lander, "Genome: Bought the book, hard to read." Recently, Professor Brendan Frey and his research team discovered a fundamentally new view of how living cells "read the genome" and use a limited number of genes to generate enormously complex tissues such as the brain. In a paper that was published in the May 6, 2010 issue of *9 WÆÔÉ* and featured on its cover, Dr. Frey describes research conducted by his team. They developed a computational technique based on probability, statistics and machine learning and used it to reveal a second level of information hidden in the genome that can account for the exponentially greater complexity required to create a human being. The work of Dr. Frey's team was reported in the - *©eÉ‰ W¥y‰W©*the *Hð/∂≤Ê%ÊW*, on CBC Radio, BBC Radio and in a variety of other national and international news. Dr. Frey leads an ongoing, multi-year project whose goal is to infer the coding mechanisms underlying the regulation of genes. The project involves experimental collaborators from the Centre for Cellular and Biomolecular Research at the University of Toronto, along with international collaborators. Several of the students and postdoctoral fellows who have graduated from Dr. Frey's lab have subsequently taken faculty positions at leading universities, including UPenn, UNC and Harvard.

Genov, Roman

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Portable, Wearable and Implantable Sensory Biomedical Electronics

We are heading the Intelligent Sensory Microsystems Laboratory at the University of Toronto. Members of our laboratory conduct research on analog and digital VLSI circuits, systems and algorithms for energy-efficient signal processing with applications to electrical, chemical and photonic sensory information acquisition, biosensor arrays, brain-chip neural interfaces, CMOS imagers, parallel signal processing, adaptive computing and implantable and wearable biomedical electronics.

Goel, Ashvin

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End-to-End Data Reliability

The goal of this project is to ensure data integrity in the face of software bugs. Currently, the project is focused on improving the reliability of storage software. When storage software is buggy, it can cause data corruption and persistent application crashes. We are developing a system that ensures that storage software, such as a file system, remains consistent in the face of arbitrary software bugs. The key idea is to verify all operations that update storage at run time using a well-defined set of consistency properties.

■ ⬢ ◡ Predictable Performance for Data Analytics Frameworks

Today, cluster computing frameworks such as Apache Hadoop and Apache Spark are commonly used for analyzing large data sets. These frameworks have become popular because they allow scaling applications to a large number of nodes in the cluster, while simplifying programming by providing facilities such as task scheduling, resource management, and fault tolerance. However, today's frameworks provide unpredictable performance and scale poorly on certain input datasets and software/hardware configurations. In this project, we are working on designing cluster computing frameworks that address some of these challenges in existing frameworks.

■ ⬢ ◡ Scalable In-Memory Databases

This project focuses on improving the performance and reliability of distributed transaction processing systems. These systems require careful data partitioning, or else load imbalance across servers can cause poor performance. Such partitioning is non-trivial, because it is workload dependent. For example, skewed workloads, or workloads that have demand spikes or change rapidly, can degrade system performance significantly. In this project, we are using novel replication methods to reduce load imbalance, while minimizing the need for expensive data movement operations. Our prototype is based on an in-memory, distributed database system that takes advantage of RDMA capabilities in modern, high-speed networks to provide low-latency, high-throughput processing.

Gulak, Glenn

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● ⬢ Fully Homomorphic Encryption

Fully Homomorphic Encryption (FHE) is a recently developed quantum-secure, public-key encryption technology that enables arbitrary computations, such as addition and multiplication, on encrypted data, without decrypting the data and without requiring knowledge of the secret key. Multiplication and addition operations are precisely the operations required to perform matching operations directly on ciphertext, thus enabling secure lookup and authentication operations. Homomorphic encryption is unique in its ability to protect encrypted data while at rest, during transport and during computation, thus simplifying key management and reducing attack surfaces. Beginning with Gentry's mathematical breakthrough, presented in his 2009 PhD thesis, there has been rapid development in the theory and algorithmic implementation of homomorphic encryption schemes. However, to date, commercial homomorphic encryption applications are not yet deployed in the marketplace because of the computational requirements of the mathematical algorithms. We have developed, demonstrated and patented scalable parallel algorithms and hardware acceleration innovations that will enable lattice-based homomorphic encryption with large security parameters to be used at very high transaction rates for a wide variety of performance-demanding applications that are run in either private and/or cloud-based server environments. Future work is focused on improved parallel algorithms, new applications and next-generation acceleration techniques. References A. Khedr, P.G. Gulak, and V. Vaikuntanathan, "SHIELD: Scalable Homomorphic Implementation of Encrypted Data Classifiers," [illegible], vol. 65, no. 9, pp. 2848–2858, Sept. 2016.

Hatzinakos, Dimitrios

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▲ ⬢ ⬟ Biometrics User-Centric Sensor Networks (BUSNET)

We propose to develop an integrated security architecture to effectively and efficiently secure and protect sensitive information and data within the domain of a care enterprise, such as wireless health care and home care applications and services. Our proposal addresses the need for secure communication and authentication of personal information, which also requires enhanced privacy and confidentiality. The proposed security architecture, "Biometrics User-Centric Secure Networks" (BUSNet) will implement novel biometrics-based security solutions and technologies that can be effectively integrated into a plethora of wireless infrastructures. Specifically, this research initiative will be examining issues and developing solutions for processing of biometrics signals, biometrics registration and authentication and biometrics key generation and management, as well as biometrics-based data authentication. Implementations of the proposed architecture using specific realizations of suitable wireless Body Area Network (BAN) configurations will also be developed, examined and analyzed in collaboration with our industrial partners. The proposed security framework constitutes an effective mechanism that integrates a novel security architecture and a cost-effective networking configuration to develop a realistic, feasible and cost-effective solution for secure transmission of sensitive information, one of the most fundamental requirements of current and future health and home care services.

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⬢ Human Recognition Based on Remote Video Capture of Eye Movements and Blinking

With increasing integration of advanced technologies into our daily life, the need for reliable biometric authentication and identification systems is more pronounced than ever before, in order to improve security and privacy and to reduce the risk of circumvention. Despite high accuracy, current biometric technologies relying on particular physical features such as fingerprints, facial and iris characteristics are vulnerable to spoofing and forgery. Therefore, there is a real need for development of more reliable biometric solutions for human recognition that are able to continuously identify/authenticate people without requiring specific actions from them (e.g., placing fingers on a scanner or looking into an iris camera). In this project, we propose a feasibility study on human recognition based on remote video capture of eye movements and blinking. The proposed solution based on eye tracking data offers a more flexible design, where eye movement and blinking patterns are captured on video recordings taken from greater distance, which is non-intrusive, simpler to analyze and more difficult to spoof. Furthermore, it offers an added advantage where the same features extracted for biometric recognition can be used for determining fatigue or other physiological conditions or behavioral changes.

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▲⬣ Medical Biometrics

The cardiovascular system offers a variety of physiological signals that can be used as biometrics. While modality such as the electrocardiogram (ECG) is still relatively novel, it is increasingly garnering acceptance as a useful biometric tool, because of some unique characteristics. Existing solutions for biometric recognition from electrocardiogram (ECG) signals are based on temporal and amplitude distances between detected fiducial points. Such methods rely heavily on the accuracy of fiducial detection, which is still an open problem due to the difficulty of exact localization of wave boundaries. To avoid fiducial points detection, the signal is processed holistically, using second-order statistics. Our autocorrelation-based method is a very simple and effective approach that does not require any waveform detection. It depends on estimating and classifying the significant coefficients of the Discrete Cosine Transform (AC/DCT) or the Linear Discriminant Analysis (AC/LDA) of the autocorrelation of heartbeat signals. The AC/LDA algorithm has been incorporated into a prototype system developed at the Biometric Security Laboratory (BioSec.Lab), the HeartID. HeartID is a MATLAB-based software with various functionalities, such as user enrolment, database handles, security level adjustment and identification/verification modes of operation.

WWW.COMM.UTORONTO.CA/~DIMITRIS/

⬣ Radio Frequency Identification (RFID) Based Multi-Agent System in Banking Environment

The wide adoption and development of wireless sensing technologies for the monitoring and autonomous identification of financial activities have affected financial institutions in the past decade. However, wider utilization of RFID technologies in the banking sector has introduced challenges regarding the security and privacy of sensitive financial data. The proposed innovations and technological developments will revolutionize the banking sector by increasing efficiency, decreasing cost and provide secure and privacy sensitive financial transactions. In this work, we will deliberately build up a RFID based comprehensive framework and its application to expertly and automatically match profiles of customer and bankers according to a number of selected weighted attributes. We will develop a RFID framework which collects, communicates and manages the financial data and customer's account details securely. Moreover, this architecture will also provide automatic interpretation and classification of the data by an expert agent; for example triggering an alarm message when needed but also providing a description and suitable options for resolution of the underlying situation. Finally, we will develop an RFID enabled multi-agent system and machine learning methodology in automating the detection of unusual network behavior and frauds and to provide security against cyber-attacks by generalizing previously stored abnormal transactions.

Helmy, Amr S.

PHOTONICS.LIGHT.UTORONTO.CA/HELMY/RESEARCH

●■▲ Infrared and THz Semiconductor Lasers

The coherent radiation afforded by lasers fuels numerous applications ranging from medicine to material processing and telecommunications. In particular, semiconductor lasers offer a form-factor, efficiency and portability that have fuelled innovations in all industrial sectors. A new class of semiconductor lasers with even more distinctive features has been developed recently. Semiconductor lasers enabled by Bragg reflection waveguides (BRW) are essentially one-dimensional photonic bandgap structures that are doped in a p-i-n profile, where light is guided by Bragg reflectors with light propagating parallel to the epitaxial layers. Bragg reflection lasers enable the realization of high-power single-mode lasers and amplifiers with larger mode volumes, higher gain coefficients and stronger mode discrimination in comparison to their counterparts. Moreover, this class of novel lasers empowers applications related to nonlinear frequency conversion in monolithically integrated optoelectronic integrated circuits. This research focuses on using this class of lasers to develop high-performance single-mode lasers for realization of electrically injected monolithic optical parametric oscillators. These chip-based sources can provide continuous coverage of spectral regions, which are not accessible by other technologies such as quantum cascade lasers. Examples of niche applications served by this unique platform include sources for environmental and biomedical sensing elements in the 1–9 μm window and chip-based THz spectroscopy sources. These sources play a pivotal role in enabling high-resolution, high-sensitivity chemical sensing and environmental monitoring applications due to their superior tunability and spectral brightness. For example, certain molecules containing carbon-hydrogen bonds have infrared footprints within the 2–3 μm spectral window. In addition, H2O exhibits significant absorption features around 2.5 μm, which can be used for in-situ combustion measurements of moisture and temperature. This spectral window is not covered with quantum cascade lasers and can benefit from a broadly tunable coherent source. We were able to recently demonstrate such a source using the devices described above. In addition we are also able to develop sources with no moving parts to cover extended regions of the spectrum using a single device. As an example, efforts are underway in the group to cover the 7–11 μm window of radiation to be able to test for most known explosives.

●■⬣ Monolithic Microwave Photonics and THz Pulse Sources with Ultralow Phase Noise

Widely tunable, stable photonic-based microwave and pulse sources are indispensable for numerous fields of applications such as in telecommunication systems, radar systems and modern metrology. These sources are often bulky and require a stable RF signal source, which increases the system's cost and complexity. In addition the attributes of these sources are usually limited by the characteristics and in particular the bandwidth of the RF sources utilized. Recently we introduced a novel, simple method to generate an optical clock with wavelength tunability. The beating signal generated by two

single-mode lasers causes the modulation of the gain saturation of an SOA that is placed inside a ring laser cavity. This technique is particularly versatile in comparison to its counterparts; the repetition rate is controlled by the frequency difference between the two CW light sources, overcoming the bandwidth limitation of other techniques, which require an RF source. In addition, the operating wavelength is tuned by sweeping the central wavelength of the bandpass filter. This new technique is also cost effective and provides the possibility for hybrid integration as it consists of semi-conductor chips that can be heterogeneously integrated on an Si platform. This research enables optical pulse-trains to be generated in an all-optical setting based on gain-induced four-wave mixing in semiconductor optical amplifiers. A unique advantage of this versatile approach is the optical control it affords of the repetition rate, which can be tuned by controlling the frequency difference between the various light sources employed in the setup. Using novel designs we are able to drastically improve upon the stability of all optical techniques through injection locking. Robust and low-phase noise pulse generation in the 100s of GHz has been measured with a line-width ~1 Hz and no need for RF sources, optical stabilization or optical feedback. Recently, we successfully achieved injection locking using a 10 MHz optical frequency comb source, while utilizing an external cavity to eliminate the residual modes. Injection locking using such a low (10 MHz) optical frequency comb source enables and provides more flexibility for numerous applications.

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Monolithic Quantum Photonic Devices and Circuits

Photons, the particles of light, play a pivotal role in the emerging area of quantum information science, such as optical quantum computing and quantum cryptography. However, these futuristic-sounding technologies only exist in specialized labs; practical commercial systems are not available to date. One of the reasons these technologies have not moved into practical settings is that they need to be implemented using bulky components that are not portable and are sensitive to vibrations. Current technologies required to produce the building blocks of quantum systems do not allow a high level of integration of these components. Those include devices for the generation, manipulation and detection of paired photons that are entangled. These entangled photons are an essential building block for quantum systems as required by quantum mechanics. For example, the mainstream technique to produce entangled photon pairs is to use a strong laser beam to hit a nonlinear crystal. With a probability of 10^–10, a photon in the laser can be converted into a pair of entangled photons. Such a system is extremely inefficient and very energy-consuming. Besides, the whole system, including the laser, nonlinear crystal, mirrors and lens, etc., takes a big space on an optics table. The optical setup requires delicate construction and is sensitive to external environment. Thanks to recent breakthroughs by our group, fully integrated, portable and robust entangled photon sources were made possible using mainstream semiconductor technologies. We successfully demonstrated the generation of entangled photons from a semiconductor chip. This electrically powered, alignment-free chip is specially engineered, which not only increases the photon generation efficiency compared to the bulk crystal counterparts, but also makes the integration with other optical components possible. Meanwhile, our group has been working on engineering the generated photon properties on the same platform to enable quantum computing, material spectroscopy, and quantum imaging, among other applications. Ultimately, our techniques will allow the entire photon generation and manipulation processes to take place on the same chip, which could be a big step towards a practical, commercial quantum computer and other quantum information processing systems.

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Nanophotonic Devices and Networks

Nanophotonics research in the group focuses on novel hybrid plasmonic-based optical devices for integrated optical circuit and signal processing. With enhanced light–matter interaction, sub-wavelength footprint, and minimal parasitics, plasmonic devices are promising candidates for next-generation opto-electronic components that can help alleviate the latency and power dissipation bottlenecks in current VLSI technologies. Utilizing plasmonic devices to enable dense, on-chip optical integration, our research also explores reconfigurable hybrid plasmonic network structures consisting of 2D arrays of intersecting waveguides. By manipulating the network topology and therefore the interference between plasmonic waves propagating among the interconnected waveguide junctions, the network can be engineered to support different spectral responses at various output ports. Moreover, by introducing functional materials such as polymer or 2D alternatives with gate-variable properties, the dispersion characteristics of the structure can be reconfigured via biasing. We are currently investigating programmable plasmonic components for optical switching and signal processing. To reduce the computational cost associated with numerical simulations, our research also involves constructing analytical models for these plasmonic network structures. Specifically, we analyze the power distribution within intersecting plasmonic waveguides through impedance analysis and a scattering matrix model. This allows the output response of networks with any arbitrary topology to be encapsulated into closed-form expressions that do not require numerically-extracted parameters. Finally, although plasmonic components can provide the field confinement necessary to support dense integration, the significant light attenuation due to Ohmic damping fundamentally limits the device performance. Our research looks to overcome this challenge through long-range, coupled plasmonic waveguide structures. By engineering the field symmetry across a common metal layer within coupled waveguide systems, we have demonstrated that the Ohmic dissipation can be minimized regardless of waveguide configuration or material platform. As a result, a radically improved attenuation–confinement trade-off can be achieved, in comparison to common types of plasmonic waveguides proposed to date. This design approach provides a powerful tool for developing a broad range of plasmonic devices such as modulators and photodetectors with small footprint and low insertion loss.

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▲ Nondestructive Analysis of Liquid-, Gas- and Aerosol-Phase Nano- and Biomaterials in Optofluidics Using Optical Spectroscopy

Conducting Raman spectroscopy in hollow-core optofluidics such as photonic crystal fibres (HCPCFs) results in significant Raman intensity enhancements compared to direct sampling in cuvette. This platform can be used as a useful method for ultrasensitive detection of vibrational modes of chemical and biological molecules. The enhancement technique in all liquid-core waveguide platforms is mostly based on their use as a waveguide to confine both the liquid and the optical field over a long distance, and the degree of enhancement attained for a specific solution depends on the physical parameters of the waveguide. The great potential of hollow-core photonic bandgap optofluidics for optical sensing originates from the increased light–matter interaction volume and efficient accumulation of the Raman scattering along the extended length of the waveguide. The well-confined excitation interacts directly with the sample molecules while propagating along the length of the waveguide and Raman scattering can be efficiently excited along the fibre's entire length. In our research we utilize different optofluidic techniques for enhancing the retrieved Raman/FTIR signal of nanomaterials in liquids, gases and aerosols. Unprecedented details in analyzing various nanostructures and biological molecules utilizing optofluidic fibres such as photonic crystal fibres (PCFs) in Raman spectroscopy have been achieved. Techniques and applications to combine surface-enhanced Raman spectroscopy (SERS) with optofluidic-assisted Raman spectroscopy to enable nanomolar sensitivity of nanolitre volumes are also being examined. Recently a detailed, non-destructive characterization of CdTe nano-particles was carried out using Raman spectroscopy for solutions with QD concentration of 2 mg/mL, which is similar to their concentration during the synthesis process. Our platform allows clear vibrational modes corresponding to the structure and interactions of the QDs to be observed. These vibrational modes include those of the CdTe core, Te defects, CdSTe interface, thiol agent and carboxylate-metal complexes. These modes are correlated with the crystallinity of the QD core, interfacial structure formed upon stabilization, QD–thiol interaction mechanisms, water solubility of the QDs and their potential bioconjugation abilities.

Herman, Peter

PHOTONICS.LIGHT.UTORONTO.CA/LASERPHOTONICS

▲ Guided Light, Tightly Packed: Novel Concepts, Components and Applications

A multi-institutional and international (Canada-Germany) training program is proposed around advances in controlling the flow of light. Three collaborating Canadian institutions (U of T, INRS, ULaval) are partnering with the German institutes of Friedrich Schiller University Jena (FSU) and Fraunhofer Institute of Applied Optics and Precision Engineering (IOF). The Canadian institutions represent the leading optical research-training centres in Canada, which in turn support a fledgling Canadian industry and service sector in optics. The German institutions define the central hub for optics education, training and industry in Germany, opening doors for our trainees to connect forefront science with manufacturing innovation. The training rationale seeks to lift PhD students out of research "silos" that naturally are shaped by the limited resources and expertise found within individual labs, and enable higher-impact research objectives that can harness the fuller spectrum of research expertise, advanced tools and resources provided by our multi-institutional team. Our CREATE philosophy is to drive this research with strong exposure to current industry practices, and participation in market-driven research activities through interaction with small and large Canadian industry and government partners. The key strategy with our German collaborators is to engage Canadian trainees early in their studies in a world-leading place for optics education and manufacturing — Jena — The City of Lights. Trainees will participate in the highly acclaimed Fraunhofer model for technological innovation (IOF) and engage in German industry internships. The program will expose trainees to a much broader research experience, where research tools and resources will appear unlimited and where ideas can be tested and shaped amongst world-leading experts with exceptional breadth in optics. The pathway ensures trainees will not only become future world leaders in optical research, but also be moulded for creativity, innovation, technology transfer and commercialization of new optical devices, advanced manufacturing processes and more functional products with promising benefits to multiple facets of Canada's manufacturing, communication, health and security sectors.

▲ Laser-Fabricated 3D Optical Interconnects for Multi-core Fibre to Silicon Chip

High-density three-dimensional (3D) optical circuits will be designed, fabricated, integrated, packaged and tested at the University of Toronto (Prof. Herman Group) by combining silicon-photonic (Si-P) chips with 3D glass chip waveguides (WG) and multicore fibre (MCF) input/output (I/O) ports. Femtosecond laser direct writing in optical glasses will enable formation of three-dimensional optical circuits as well as nanostructures to guide 3D chemical etching to microstructure the glass block. Both the University of Toronto and Huawei will provide Si-P chips to test and verify various design approaches in chip-to-chip interconnection. The research will examine the compatibility of edge coupling (EC), grating coupling (GC) and adiabatic coupling (AC) for high-density, low-insertion packaging between high-index chips (Si, Si/InP, etc.) and MCFs.

▲ Quantized Structuring of Transparent Film and Plates with Ultrafast Laser Interference and Filamentation

Nano-structuring of materials is the basis of rapidly expanding application areas where ultrashort lasers are becoming a tool of choice with benefits of non-contact processing that precisely shapes and patterns with very little residual damage. Short-pulsed lasers further underpin a unique capability for 3D structuring inside transparent glasses. In this direction, a new research project is proposed around our recent discovery of a novel laser interferometric interaction discovered in silicon-nitride film that underlies a new means for laser material nanostructuring. Here, optical interference fringes are formed parallel with the surface that for the first time can create thin

laser plasma disks and form lateral modification zones, nanocavities, thin blisters and quantized ejection from interaction zones substantially narrower than is possible even when focusing with high-resolution lenses. This new means of control has not been previously anticipated, and is especially attractive in high-temperature dielectric media like optical films that find widespread use in processing microelectronic, optical, lab-on-chip, photonic, MEMs and photovoltaic devices. The research program will improve our fundamental understanding of how the interference and other nonlinear processes such as self-channelling can play together in transparent films and plates and serve as a basis for developing new nano-optical devices and forming novel nanostructured glasses. Reproducible manufacturing methods are pursued with two industry partners in directions that include bio-inspired concepts to strengthen windows for low-weight sunroofs, inventing new types of anti-reflection surfaces and compact microlens arrays, and providing three-dimensional volume texturing for improving adhesion, wetting, or biosensing. Alternatively, ultrathin membranes offer new ways to package materials or sense mechanical properties. Lastly, quantum laser interaction offers the opportunity for generating complex multilayered nanofluidic networks inside thin film that may permit flexible lab-in-film devices to be integrated with smart phones, cameras or microelectronic chips.

Spatio-Temporal Polarization Control of Ultrafast Laser Interactions

Nanoscience and nanotechnology are evolving with the new physical laws encountered as the structures and devices we make become smaller. Quantum-level effects manifest in new ways to manipulate electrical, magnetic, optical, mechanical – virtually all – properties of materials in surprising but exceedingly useful ways. Optical physics and quantum optics have embodied these trends to push resolving power well below the classical diffraction limit in areas of near-field, confocal, plasmatronic and multiphoton microscopy, prompting a Nobel Chemistry Prize in 2014 for super-resolution optical microscopy. Such tools are opening the frontiers of nanoscience by enabling the formation, interrogation and manipulation of nanostructures down to the size of single molecules, while laser projection lithography has come to define the nanotechnology forefront for high-volume manufacturing of microelectronic chips with transistor gate widths of 10 nm – just a few atoms thick. In this race to shrink the world, our program is seeking to understand and harness the new optical phenomena found in nanostructures much smaller than the wavelength of light. Beginning in the domain of linear optics, novel types of optical materials with unusual photonic bandgap, metamaterial, or plasmatronic properties have been developed that reshape how light can propagate or reach below conventional diffraction limits with powerfully enhanced optical resolution. The advent of high-power lasers with extremely short duration pulses has accelerated the study of nonlinear optical interaction physics. High-brightness light poses significant questions when propagating inside bulk transparent and nanostructured media, becoming “self” manipulated by the nonlinear response of the medium, while also receiving resonance feedback in the proximity of nanostructured media. Such nonlinear interactions define a new, unexplored opportunity for manipulating the phase and absorption response that we aim to study and control with new spatio-temporal polarization tools. Our program proposes various modes of amplitude, phase and polarization shifting to create novel beam shapes and patterns — non-diffracting (Bessel), vortex, ‘self-accelerating’ — and harness advanced real-time characterization tools such that the non-linear absorption, Kerr-effect, plasma response, phase explosion and shock physics can be followed in transparent media and eventually be controlled to drive open new manufacturing methods for photonics, biology and medical devices.

Hooshyar, Ali

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Cyber-Security of Power Grid Protection Systems

Smart grid initiatives have led to more reliable power systems by providing access to useful data captured from across the grid and enabling remote protection and control of the system. These features are made possible through an extensive communication network, so they come at the expense of exposing the grid to various cyber vulnerabilities. If a cyber-attack manipulates the data transmitted to or from the protective devices, it can result in various protection malfunctions with serious consequences. Multiple studies have concluded that the communication networks of the power systems are not prepared to cope with the existing cyber threats. A variety of information security methods — such as sophisticated data encryption techniques — have been developed to secure the communication networks of power systems. However, cyber-attacks have continued to threaten power system operation despite the improvement in the performance of these security tools. Therefore, our group is working on devising application-based security methods for protection systems. These methods use the physical/mathematical relations between different measurements in a power system to detect anomaly in the data received by the protective devices through communication networks.

Microgrid Protection

Our research falls in the general area of protection and control of renewable energy systems and smart grids. The main objective of our research is to improve the resilience and sustainability of the power grid. The legacy power grid has top-down architecture from the generation to transmission to distribution systems. Thus, large-scale disruptive events (e.g., superstorms) that affect the transmission system can potentially result in loss of many distribution systems. The slow recovery process under such conditions limits the grid resilience. Within the past decade, however, abundant integration of renewable energy sources with distribution systems led to the emergence of microgrids. A microgrid can supply the loads when it is islanded from the grid. Hence, the grid resilience is improved substantially by preventing the outages caused by disruptions in the transmission system. However, the resilience offered by a microgrid will be in jeopardy if it is not properly protected during the faults that occur within its own boundaries. Microgrid protection is a formidable task due to the unconventional fault behaviour of renewable sources, variable short-circuit currents, etc. We are currently developing a new microgrid protection system that can address the adverse effects of renewable sources during faults and disturbances.

Hum, Sean

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● Efficient Numerical Analysis Techniques for Advanced Electromagnetic Surfaces

Next-generation antennas are being realized from novel technologies based on advanced electromagnetic surfaces, such as reflectarrays, meta-surfaces, and frequency-selective surfaces. These surfaces are very large and yet contain very fine features, making them challenging to design and analyze in conventional Computer-Aided Design (CAD) tools. This project is investigating computationally efficient yet accurate techniques for analyzing such surfaces. The approach is based on a macro-modelling-based method for encapsulating fine features with a coarse-grained model, to yield major savings in computation time and resources.

●▲ Material-Centric Design of Advanced Electromagnetic Surfaces

Advanced electromagnetic surfaces (AESs) have enabled the development of exciting new antennas and components for wireless communications, owing to the ease with which they achieve extraordinary control of electromagnetic radiation. They are indispensable for realizing directive and adaptive antennas, which are cornerstones of future systems such as 5G. Despite advances in AES-derived antennas, their impact will not be fully realized until they simultaneously achieve greater bandwidth, reconfigurability, efficiency, and — critically — overall ease of design. This research project puts forth a new material-centric design methodology for AESs that views them as materials that can be designed using material-informatic techniques to replace current adhoc and trial-and-error–based design methods for AESs.

● Multibeam Reflectors for Satellite Applications

Realizing multibeam apertures on satellite platforms while satisfying volume, mass and cost requirements is extremely challenging, resulting in a wide array of competing architectures for multibeam systems employing a single feed per beam. Spatially fed antenna arrays offer numerous advantages in this space, including low mass, low profile and, importantly, the ability to provide fine control over the scattered signals at different frequencies and polarizations. This creates a compelling case for investigating the use of this architecture in multibeam satellites. This project is exploring various architectures for realizing these antennas for next-generation broadband telecommunication satellites.

●▲ Reconfigurable Leaky-Wave Antennas

This project is exploring the creation of very-low-profile 2D apertures which can be efficiently fed using an internal feed. As such, they can potentially offer the gain and flexibility of reconfigurable reflectors and lenses without the bulk associated with those architectures. Instead, radiation is produced through purposefully tailored leakage from surface waves travelling within the aperture. Active devices can be embedded in the aperture to provide full phase control of scatters embedded within the aperture. The result is a flat and potentially low-cost beamforming platform that can be used in a variety of applications, such as RADAR, satcom-on-the-move, rail signalling and others.

● Reconfigurable Spatially Fed Arrays

This project is developing spatially fed arrays, such as reflect-arrays and array lenses, for aerospace applications. The goal is to create very flat and thin antenna apertures that can be electronically scanned and that exhibit much wider bandwidths than are possible with conventional implementations of these architectures. At the same time, spatially fed architectures provide a high-performance, cost-effective alternative to traditional phased arrays. Applications include point-to-point communication systems, satellite systems (particularly satcom-on-the-move), radar, and remote-sensing systems.

Iizuka, Keigo

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▲⬟ Noble Laparoscopes

Laparoscopic surgery is a less intrusive procedure than open surgery. The post-operative pain is less, the infection rate is lower, recovery is quicker and cosmetic outcome is better. As a natural extension of the earlier invention of Divcam (distance mapping camera), two applications of Divcam have been extended into the field of laparoscopy. (1) Application of Divcam to profilom. Images from ordinary laparoscopes and endoscopes are two dimensional (2D), meaning the surgeon's depth perception is hindered. The proposed method supplements the 2D image with an image of the depth profile of the surface. The depth profile is obtained in real time without surface contact. The profilometer uses the same principle for acquiring distance information as Divcam. The profilometer was added to an ordinary laparoscope with minimal increase in the weight and diameter of the shaft. With the profilometer added, there was a significant improvement in the ability to detect minute protrusions. It can detect a protrusion as small as 0.5 mm high that would not be recognized by an ordinary laparoscope. K. Iizuka, ≈≈Œý‰≈Ê› , vol. 52, no. 19, pp. 4663–4671, July 2013. (2) Application of Divcam to omni-focus laparoscope. The depth of focus of a laparoscope, even the latest model, is limited to 10 cm. The proposed omni-focus laparoscope has stretched its depth of focus to 160 cm. Omni-focus means that everywhere, not just the designated spot in the video, is in focus. This property is significant in the case of a laparoscope. The entire scene, not just a specific spot, must be focused during the surgery. The proposed omni-focus laparoscope is equipped with an array of colour video cameras, each focused at a different distance. The distance information from the laparoscopic profilometer is used to select individual pixels from the ensemble of outputs from this array of colour video cameras and generates the final single "omni-focused" laparoscopic video image. The experimental results clearly demonstrate how significantly the quality of the image of the omni-focus laparoscope differs from that of a conventional laparoscope. K. Iizuka, ≈≈Œý‰ ; ≈Ê› , vol. 52, no. 33, pp 7904–7911, 2013.

▲ Omni-Focus Video Camera

Our major achievements during the recent past were the invention of two novel types of distance-mapping video cameras. The first invention, called the Axi-Vision Camera, is a distance-mapping camera that is based on the combined principles of time of flight and modulated light illumination. Television programs produced by using the Axi-Vision Camera have been broadcast from NHK, Japan. In a contest sponsored annually by ; ≈Ê¢› %‰Cü∂Ê≤¢› %‰É ˆ › of the Optical Society of America, the paper on the Axi-Vision Camera was selected as one of the most significant scientific accomplishments described in a refereed journal in 2002. The Axi-Vision Camera was commercialized by NHK Enterprises, Japan and the first unit was sold for $400,000. We received the 2003 Fujio Frontier Award in recognition of our leading-edge research and development of the Axi-Vision Camera. The second invention, called the Divcam (short for Divergence Ratio Axi-Vision Camera), is a distance-mapping camera that utilizes the universal decay rate of the illuminating light with distance. The Divcam is lightweight, compact, portable and reliable, has a fast response and is low cost: a U.S. patent was filed on the Divcam and later extended to an international patent through the Patent Corporation Treaty. The omni-focus video camera, which needs the information of distance, was invented as a natural extension of the Divcam. Its invention was reported by various news organizations and magazines, including Fox News Network in the U.S. Some media even stated that the omni-focus video camera would revolutionize the global camera industry. Recently, the omni-focus video camera was used to obtain a super deep 3D image. The article “Super Deep 3D Images from a 3D Omnifocus Video Camera” highlighted this achievement: the image appeared on the cover of the February, 2012 issue of the journal ≈≈¢Éy‰≈Ê¢› .

Iravani, Reza

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Battery-Enabled Electric Vehicle DC Fast-Charging (DCFC) Technologies and Systems

This research addresses operational and control aspects of the DC microgrid, which supplies multiple Level-3 DCFC units mainly from a grid-level battery unit, during both grid connected and islanded modes of the DC microgrid. The DC microgrid reduces/eliminates fast-charging stress on the host AC grid and replenishes the grid-level battery from the grid spare capacity.

Control, Operation and Energy Management of Hybrid AC-DC Microgrids

This RD&D project addresses the challenges, strategies, solutions and technologies for monitoring, protection, control, and operation of (1) utility-grade urban, rural, and remote AC microgrids subject to the high depth of penetration of renewable and alternative energy resources, and (2) DC microgrids.

Modelling, Analysis, Control, Protection and Operation of High-Voltage Direct Current (HVDC) Systems and Medium-Voltage DC (MVDC) systems

This research addresses challenges in the development of analytical models, time-domain simulation models and control/protection strategies/algorithms for HVDC links, HVDC grids and MVDC power systems.

Real-Time Hardware-in-the-Loop (RT-HIL) Simulation of DC-AC Power Systems and Microgrids

This work includes research and development of analytical and real-time simulation strategies and the corresponding hardware/software tools for the analysis, control, protection and operation of (1) large interconnected AC power systems that embed High-Voltage Direct-Current (HVDC) grids and (2) microgrids with a high depth of penetration of distributed generation and storage units.

Jacobsen, Hans-Arno

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■ ⬢ eQoSystem: Towards Declarative Distributed Applications

The eQoSystem project seeks to simplify the development and management of business processes deployed on a distributed Service Oriented Architecture (SOA). The target architecture is an enterprise system with distributed services co-ordinated by application workflows or business processes. Declarative goals, specified in Service Level Agreements (SLAs), are used to assist in the development of such applications and to automate the monitoring, deployment and resource provisioning tasks. The eQoSystem project is conducted by the Middleware Systems Research Group (MSRG) at the University of Toronto and is a collaboration involving IBM Toronto and NSERC.

● ■ ⬢ Middleware Systems Research

We design state-of-the-art middleware systems to simplify the design, development and management of complex distributed applications. We conduct research on middleware and distributed systems at the University of Toronto. Our current research is mainly focused on publish/subscribe, content-based routing, and event processing. We see middleware as the services and abstractions that facilitate the design, development, integration, and deployment of distributed applications and systems in heterogeneous networked environments.

● ■ ⬢ The PADRES ESB: Events and Services Bus

PADRES is an open-source, enterprise-grade event management infrastructure that is designed for large-scale event management applications. Ongoing research seeks to add to and improve enterprise-grade qualities of the middleware. The PADRES system is a distributed content-based publish/

subscribe middleware with features built with enterprise applications in mind. These features include (i) intelligent and scalable rule-based routing protocol and matching algorithm; (ii) powerful correlation of future and historic events; (iii) failure detection, recovery and dynamic load balancing, and (iv) system administration and monitoring. As well, the PADRES project studies application concerns above the infrastructure layer, such as (i) distributed transformation, deployment and execution; (ii) distributed monitoring and control; (iii) goal-oriented resource discovery and scheduling, and (iv) secure, decentralized choreography and orchestration. A publish/subscribe middleware provides many benefits to enterprise applications. Content-based interaction simplifies the IT development and maintenance by decoupling enterprise components. As well, the expressive PADRES subscription language supports sophisticated interactions among components and allows fine-grained queries and event-management functions. Furthermore, scalability is achieved with in-network filtering and processing capabilities. The PADRES research project is conducted by the Middleware Systems Research Group (MSRG) at the University of Toronto and is a collaboration involving various industry partners and Canadian funding agencies.

Johns, David

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Advanced Interface Circuits for MEMS Technology

Micro-ElectroMechanical Systems (MEMS) refers to tiny devices that combine micrometre-scale mechanical devices with micro or nanoscale electronic circuits to sense physical quantities. Some recent examples of commercial applications for MEMS are pressure sensors used as microphones in devices such as cellphones and hearing aids, inertial sensors used in airbag deployment as well as positional control in hand-held games and cellphones, and gyroscopes used for image stabilization for cameras as well as angular velocity measurement in hand-held games. This research program investigates new circuits and architectures that will significantly improve MEMS power dissipation as well as improve accuracy performance. With improved accuracy, new applications can be developed that are not otherwise possible. For example, a highly accurate inertial sensor can be used to track position by integrating acceleration to obtain velocity and then integrating velocity to determine distance travelled.

Joy, Mike

IBBME.UTORONTO.CA/PEOPLE.EMERTI/MICHAEL-L-G-JOY

Current Density and Conductivity Imaging with MRI

In 1989 I initiated a research program whose goal was to create images of the electrical current density (CD) inside the body based on Magnetic Resonance Imaging (MRI). In the next five years this research was widened to include the imaging of tissue electrical conductivity. This work has resulted in two novel techniques, Current Density Imaging (CDI) and Current Density Impedance Imaging (CDII). The imaging of tissue conductivity has been a recurring objective since the 1930s. Today, the best-known method is Electric Impedance Tomography (EIT). EIT measures currents and voltages on the skin and relates them to possible conductivity distributions in the body. Unfortunately EIT is a very ill-posed problem and consequentially has poor resolution at depth. This severely limits its effectiveness. The novelty of CDI and CDII is that MRI can be used to measure the magnetic fields arising from internal electric current density and the conductivity can be accurately computed from these fields. This has been verified in my lab and internationally. This distinguishes CDI and CDII from EIT. The unanswered question is, “Can CDI and CDII give rise to a new technique that is more medically useful?” To be medically useful these measurements must be safe, accurate, of high temporal and spatial resolution and clinically feasible. Presently there are no methods that meet these requirements. We have used CDI in live animals (5-kg pigs) and spatial resolution of 2 cm and temporal (gated) resolution of 10–20 ms. CDII is accurate when conductivity is isotropic. Since tissues are typically anisotropic we are presently testing a technique combining MRI diffusion tensor imaging (DTI) and CDII (DT-CD-II). These MRI sequences are distinct from those developed by others in that CDI is accurate and does not depend on the nature of the tissues in which the current flows. The consequence is that we must physically rotate the tissues being imaged. In the long term I wish to remove or mitigate this requirement. In summary, my most recent success has been to be the first to image anisotropic conductivity.

Kherani, Nazir

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Hyperspectral Sensing and Imaging

The ability to control visible and infrared light vis-à-vis guidance and concentrated light localization below the diffraction limit can usher in remarkable sensing and imaging modalities. The objective of this project is to undertake in-depth research and development of novel nanoscale gratings that enable hyperspectral light-trapping within graded gratings using adiabatically coupled plasmonic waveguide resonators. Specifically, the goal is to explore various nanoscale designs and integrations that will permit unprecedented sensing capabilities at the molecular scale. Studies to date indicate that this technology can create a powerful adjunct for biomedical applications wherein an optical device with micron-scale footprint would be capable of mapping the chemical composition of given samples with sub-cellular resolution at extremely high speeds.

Novel Nanoparticle Material Systems

The ability to synthesize binary, ternary and quaternary nanoparticles using a non-solution-based approach opens the potential of developing novel material systems with unique properties. The objective of this project is to undertake the synthesis and characterization of novel nanoparticles developed using the Advanced Materials-Integration Synthesis (AIMS) Facility. The AIMS facility permits the combination of both physical and chemical deposition techniques where the former includes size-selective synthesis of nanoparticles.

Photonic Materials for Next-Generation Optical Coatings

Novel photonic materials and integrations provide the potential of developing next-generation optical coatings for a variety of energy efficiency applications. As an example, the buildings sector consumes approximately 40% of the total energy consumed in the U.S. (followed by the industry and transportation sectors). Of this 70% of the energy consumption in buildings is for HVAC (heating, ventilation and cooling) and lighting at approximately 50% and 20%, respectively. In this context, windows have long been recognized as a major cause of radiative heat loss and solar optical energy gain in buildings. Integration of economically effective measures necessitates advanced research on novel, high-efficiency, next-generation photonic spectrally selective energy coatings. The aim of this project is to develop novel photonic materials that embody the requirements of high performance, sustainable material system, and economic viability. Specifically, three optical applications are targeted. One, next-generation spectrally selective coatings which are inherently stable (optically and thermally), tunable vis-à-vis visible, near infrared and mid infrared, and provide integrated active heating functionality; two, radiative cooling photonic devices that avail the large transparent mid-infrared bandwidth of the atmosphere in relation to outer space; and three, novel strain-tunable active/adaptive photonic devices for a variety of applications.

Ultra-Thin Silicon Micro-opto-electronic Devices: Using Versatile Low-Temperature Fabrication Techniques

The ubiquity of silicon extends into both electronic and optical devices. Within the framework of energy generation, silicon solar cells continue to dominate the field. While confronted by new emerging solar photovoltaic materials and devices, silicon continues to rise to the challenge with scientific advances and technological enhancements. Perhaps the next holy grail is ultra-thin silicon micro-opto-electronic devices with versatility in fabrication, particularly at low temperatures, while preserving or promoting the highest level of performance. From an energy generation perspective, silicon PV would benefit from advances in ultra-thin (≤10 microns) high-efficiency silicon PV—rendering the benefits of pliable, lightweight, durable, economical and ubiquitous photovoltaic electricity. Further, it is conceivable that micro-opto-electronic circuits could also benefit from this platform with an eye to “more than Moore.” The objective of this project is to research, develop and integrate a set of thin-film and allied versatile and low-temperature fabrication techniques that will lead to the demonstration of high-performance micro-opto-electronic devices based on ultra-thin silicon foils.

Khisti, Ashish

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Low-Delay Communication Systems for Streaming Media

We investigate theoretical foundations and practical architectures of communication and compression techniques optimized for low-latency applications such as conferencing and cloud computing. It turns out that traditional methods that separate compression and error correction into different modules are far from optimal when end-to-end latency is considered. Furthermore, the instantaneous dynamics of the communication channel play a fundamental role in the ultimate performance limits of low-latency systems. Therefore both the theoretical approaches and resulting architectures for low-latency communication systems are radically different from traditional approaches to reliable communication systems. The proposed project tackles this challenge in collaboration with Hewlett Packard Laboratories.

Kschischang, Frank

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Coding and Modulation for Data-Centre Fibre-Optic Communications

We are investigating information-theoretic limits and coded-modulation schemes for Stokes-vector direct-detection receivers in short-range (<100km) high-speed optical communication systems useful for data-centre applications.

Coding for Resistive Memories

We are investigating efficient coding schemes for information storage in resistive memories organized in multilayer crossbar arrays. This involves combinatorial analysis (counting the number of essentially distinguishable patterns) for a given array size, as well as the design of appropriate encoding and decoding functions.

Fibre-Optic Communication Using the Nonlinear Fourier Transform

Fibre-optic transmission systems are evolving at a rapid pace towards achieving greater spectral efficiencies. Coherent detection is supplanting non-coherent detection and polarization multiplexing and advanced modulation schemes are being implemented. Today’s high-speed electronics enable very sophisticated signal processing and coding to be applied, even at extremely high data rates, yet there is a significant gap between what has so far been practically achieved and what is known to be achievable in theory. In this work we study information transmission techniques based on the nonlinear Fourier transform. The nonlinear Fourier transform (NFT), a powerful tool in soliton theory and exactly solvable models, is a method for solving integrable partial differential equations governing wave propagation in certain nonlinear media. The NFT decorrelates signal degrees-of-freedom in such models, in much the same way that the Fourier transform does for linear time-invariant systems. In the proposed communication scheme, which can be viewed as a nonlinear analogue of orthogonal frequency-division multiplexing commonly used in linear channels, information is encoded in the nonlinear frequencies and their spectral amplitudes. Unlike most other fibre-optic transmission schemes, this technique deals with both dispersion and nonlinearity directly and unconditionally without the need for dispersion or nonlinearity compensation methods. Much work remains to be done, however, in translating this theoretical idea into practice.

Spatially Coupled Algebraically Decodable Codes for High-Speed Data Transmission

Optical fibres support very high-speed communication channels (hundreds of Gbits/s per wavelength) and designing error-control coding schemes that can correct channel errors at such high speeds is a daunting task. This research investigates one promising family of codes, so-called spatially coupled algebraically decodable codes, for such applications. This family includes "staircase codes," a hardware-friendly class of codes with excellent code performance. Our ongoing research is investigating methods to incorporate soft-decision information and to combine coding with higher-order modulation.

Kundur, Deepa

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Advanced IT/OT Convergence Methods for Secure Power Grid Control

Critical energy infrastructure is undergoing a "cyber-enablement" through the integration of information technology (IT) such as advanced sensors, communication networks and computational devices with operational technology (OT) that monitors and controls power delivery. The increased dependence on IT has advantages of improved efficiency, sustainability and reliability, but at a cost of vulnerability to cyber-attack. Cyber security of such infrastructure is challenging given the geographic scale, volume of data and complex interdependencies that exist within these systems. In addition, current security practices are siloed between IT and OT domains due to their distinct evolutionary pace, life cycles, drivers and organizational domains. In this project, we develop advanced threat detection and defence systems for the power grid within an IT/OT convergence framework that builds on existing security practices. IT/OT convergence refers to the integration of systems, processes, data and people from the information and operational environments under one umbrella, providing opportunities for improved situational awareness. As such, the outcomes of this proposal include mechanisms for more accurate and faster threat detection of emerging power grid attacks using combined IT/OT data and coordinated defence strategies based on machine learning and responsive control that limit the impacts of an attack on both IT and OT domains. Research results will be designed and tested in collaboration with Hydro-Québec Research Institute using their advanced testbed facilities. This proposal is aligned with Canada's Cyber Security Strategy and the National Strategy and Action Plan for Critical Infrastructure. The health and happiness of a society is coupled to its national security. Critical energy infrastructures represent a cornerstone of a nation's well-being. The proposed project supports a strengthened society in which Canadian academia and industry can collaboratively participate in its protection, creating tools and training highly qualified personnel for its continued safety.

Cyber-Physical Protection of the Smart Grid

The emerging smart grid represents an engineering system with tightly coupled and co-ordinated cyber and physical components. The close interaction of such diverse components may lead to emergent system behaviours and new forms of vulnerabilities. However, opportunities may also exist through the coupling to improve system survivability in the face of faults and attack. This research program pioneers the development of a modelling and analysis methodology for cyber-physical smart-grid systems by harnessing the power of dynamical systems frameworks. Through integration of mathematical tools from the fields of nonlinear dynamical systems, graph theory and game theory, we aim to address timely and important system operation, control and security problems influenced by the needs of electric power utilities. The work will provide timely design insights and instruments essential for developing more reliable, secure and survivable smart grids. Solutions for resilient smart-grid development and operation are just emerging and the proposed research provides a necessary framework to better assess, redevelop and prioritize them. Moreover, this research helps to reinforce the synergy among communication, computation, economic and electricity networks, fostering an important interdisciplinary view of the emerging smart grid. The ability to build resilient smart-grid systems will provide commercial and environmental benefits by facilitating widespread adoption of smart-grid infrastructure, revolutionizing the electricity marketplace and reducing our society's ecological footprint.

Cyber-Security Enhancement for Smart Grids Using an IT/OT Convergence Approach

The December 2015 cyber-attack against Ukraine's power grid revealed the developing capacity of energy infrastructure attackers to manipulate and to spread their actions across a variety of systems in both information technology (IT) and operational technology (OT) domains, such as business networks and supervisory control and data acquisition (SCADA) systems. Traditional security approaches relying on siloed IT security, OT security and physical security programs have become increasingly unable to deter such advanced cyber attacks. Moreover, despite ensuring conformity to different security standards and regulations, traditional security approaches potentially run the risk of becoming inefficient against evasive and dynamic threats that can bypass classic solutions. Hence, a new approach is needed in order to bridge the security gaps resulting from the divergence of IT and OT in energy infrastructures. This divergence stems from disparate technical realities (such as different evolution pace, life cycles, and drivers) and organizational aspects (dictated, for instance, by the fact that IT and OT teams are often associated with different administrative entities and follow different regulations). As a result, no collaborative security approaches have been tailored to solve cyber-security incidents by jointly involving IT, OT and physical security teams. The main objective of this project resides in developing a new converged security approach that not only leads to more collaborative solutions but also to more advanced ones, using a broader variety of defences and network management tools.

Smart Grid: Cyber-Physical Operation, Security and Quantum Technology

Future electricity generation and distribution networks will be enormously sophisticated. They will incorporate the ever-increasing renewable sources of energy (e.g., solar, wind, hydro) in a most cost-effective and energy-efficient way; they will need to be robust and resilient in the event of a natural

disaster or a malicious attack; and they will enable competing firms to share the same physical and cyber infrastructure while protecting the private usage information of millions of individuals. In short, the networks will have to employ advanced sensing, computation, and communications mechanisms to enable efficient and flexible generation, transmission, and distribution of power through a grid — a smart grid. We propose to build a research infrastructure platform to study the control and communication of a large-scale smart grid. A salient feature of the proposed infrastructure is the incorporation of a physical quantum network, reserved for the most critical part of the smart-grid communication, where security, authenticity, and latency of information exchange are critical to system monitoring and control. The project consists of four carefully crafted components: (i) the development of a hardware-in-the-loop real-time simulator platform for large-scale smart grids employing in-house FPGA-enabled Real-Time Digital Simulator (RTDS) systems that provide fast and reliable study of complex power systems; (ii) the design of a real-time heterogeneous smart-grid communication network simulator that enables the dynamic study of practical communication constraints and a variety of cyber attacks at different network layers along with a defence-in-depth approach for protection; (iii) the construction of an information-theoretically secure physical quantum key distribution (QKD) network, consisting of commercial QKD systems as well as a newly proposed measurement-device-independent QKD system, to be custom built in house; and (iv) the overall integration of the first three components to produce a dynamic real-time large-scale testbed test, the first of its kind, facilitating unprecedented insights into smart-grid integration and operation.

Kwong, Raymond

WWW.CONTROL.UTORONTO.CA/PEOPLE/PROFS/KWONG

Security and Fault Tolerance of Cyber-Physical Systems

Critical infrastructures such as power grids, water supply systems, and traffic networks are referred to as cyber-physical systems. One key requirement for such systems is security from malicious attacks, often in the form of cyber attacks aimed at compromising supervisory control and data acquisition systems. The second key requirement is fault tolerance: the ability of the control system to continue functioning despite component failures. Component failures can occur as a consequence of malicious actions by an attacker, but can also occur as a result of hardware breakdown or unforeseen operating conditions. Most approaches to combat cyber attacks focus on prevention through firewalls. Ubiquitous connectivity and stealth technologies have rendered preventing access and detecting intrusion increasingly difficult. Traditional approaches to fault-tolerant control design are also inadequate as they often rely on first carrying out accurate fault diagnosis, followed by control reconfiguration. The system may be damaged or irrecoverable while waiting for diagnostic information. The proposed research aims to improve the security and fault-tolerance of control systems central to cyber-physical systems. The two main objectives of the proposed research program are to develop a novel methodology to detect malicious intruders and prevent them from inflicting damage to the control system, and to maintain functionality and safe operation of control systems when components fail. The first objective focuses on security at the system level. Our approach will make use of the theory of supervisory control and diagnosis for discrete event systems to perform intrusion detection and to counteract malicious behaviour. The second objective focuses on resilience of the control system at the physical level when actuators and/or sensors fail. The novelty of our approach is that we focus on fault-tolerant control design, which does not require accurate diagnostic knowledge. We propose to study fault-tolerant control as an integrated problem of diagnosis and control reconfiguration, emphasizing the interaction of these two modules and exploiting available analytical redundancies. Protecting cyber-physical systems is of great national interest. The proposed research can provide significant improvements in the security and resilience of cyber-physical systems.

Lehn, Peter

WWW.ELE.UTORONTO.CA/LEHN

Power Electronics to Enable More Sustainable Electrical Energy Networks

Professor Lehn's research activities encompass on-board power electronics for electric vehicle drivetrains and charging, power converters for AC and DC microgrids along with their local and systems-level controls and utility-scale power electronic systems for energy storage, FACTS and HVDC transmission. Of specific interest is the development of network architectures and requisite power electronic conversion systems that provide lower-cost and lower-loss integration of renewable energy sources, stationary energy storage and plug-in electric vehicles. Improving robustness and power quality of the electrical grid via intelligent control of power-electronically interfaced sources and loads is an additional area of interest.

Leon-Garcia, Alberto

HTTP://PORTAL.CVST.CA

Connected Vehicles and Smart Transportation

The project on Connected Vehicles and Smart Transportation (CVST) is a collaboration between industry, government and academia to develop an information gathering and sharing platform to enable smart applications for transportation and transit in the public and private domains. The CVST system leverages the sensing capabilities of mobile devices and public-sector sensors to provide real-time state information that is enhanced by analytics to enable users and applications to make decisions that reduce travel time, increase productivity and reduce energy consumption and vehicle emissions. A live portal showing the state of traffic in the Greater Toronto Area is available at portal.cvst.ca. The CVST platform is currently being deployed in smart city projects.

Design of Next-Generation Smart Infrastructures and Service Platforms

The convergence of three technologies — cloud computing, software-defined networking, and Internet of Things (IoT) —

provides an opportunity to create application platforms that offer unprecedented technical capabilities, scalability, energy efficiency, security, flexibility, and economics. Cloud computing provides on-demand computing power for applications at unprecedented price points. Software-defined networking allows flexible network equipment to be tailored to the needs of applications. IoT allows sensor and control devices to be attached to the Internet in support of new applications. In combination, these three technologies enable applications that are smart in the sense of being aware of context as well as the state of the environment. These applications will be used to manage resources in smart infrastructures (transportation, power, water, air quality, buildings, etc.). They will also provide novel services, such as a personal assistant that is aware of context, activity schedule, and the goals of an individual. We view computing and communications resources as organized in multiple tiers, with remote massive data centres at the heart of the cloud, a smart edge providing telecom services, and then a fog consisting of gateways and sensor and actuator devices. Creating and deploying applications across this multitier cloud is challenging because of the variety of diverse technologies and incompatible protocols. Our research focuses on the design of management systems that span the cloud, smart edge, and fog to coordinate the allocation of resources to applications.

WWW.SAVINETWORK.CA

Smart Applications on Virtual Infrastructures (SAVI)

The SAVI testbed (Smart Applications on Virtual Infrastructures) is the outgrowth of a partnership between Canadian industry, academia, government, education research networks and high-performance computing centres. SAVI was developed to prove the concept of a virtualized, converged computing and communications infrastructure to support the rapid deployment of large-scale distributed applications. A key innovation in SAVI is the notion of a Smart Edge that complements remote data centres to build a multitier cloud that leverages cloud computing and software-defined networking. SAVI has designed and deployed a seven-node national testbed to support experimentation in future Internet protocols and architectures as well as future large-scale applications. The SAVI testbed is federated with the U.S. GENI testbed for network innovation and an additional node operates in Korea. The current focus in SAVI is to incorporate Internet of Things at the edge to support experimentation in smart city research.

Levi, Ofer

WWW.BIOPHOTONICS.UTORONTO.CA

Optical Biosensors and Biomedical Imaging Systems

Our main fields of interest include biophotonics and semiconductor optical devices, and, in particular, the development of miniature optical biosensors and biomedical imaging systems enabled by semiconductor optical devices and nanostructures. We seek to design, fabricate and use miniature optical imaging systems for portable microfluidics diagnosis systems and for in vivo applications such as optical brain imaging and continuous monitoring of tissue kinetics and vital signs.

Recent projects include: (1) Optimizing miniature optical biosensors based on nanostructures and small optical cavities for sensitive all-optical ultrasound detection. (2) Developing portable optical and photoacoustic imaging systems for biomedical diagnosis and therapy tracking inside the body (in vivo imaging). (3) Remote imaging of patient physiology and vital signs using portable and smart 3D cameras. Our lab collaborates with research labs and with physicians at Toronto's hospitals, to translate our studies and apply the imaging systems we develop to disease monitoring and patient care.

Li, Baochun

IQUA.ECE.TORONTO.EDU/SPOTLIGHTS/DATACENTER.HTML

Bandwidth Allocation in Datacenter Networks

Web service providers like Google and Facebook have built large-scale datacenters to host many computationally intensive applications, ranging from PageRank to machine learning. In order to efficiently process a large volume of data, these applications typically embrace data parallel frameworks, such as MapReduce. It is commonly accepted that bandwidth in datacenters should be shared in a fair manner. We have proposed the notion of performance-centric fairness that is specifically customized for bandwidth allocation among data parallel applications in private datacenters.

IQUA.ECE.TORONTO.EDU/SPOTLIGHTS/SCHEDULING.HTML

Fair Scheduling in Cloud Datacenters with Multiple Resource Types

In the age of big data, it has been the norm for cloud datacenters to run data analytic applications on a large scale. Yet, as multiple applications share resources in these datacenters, it is important to design scheduling disciplines so datacenter resources are shared in a fair and efficient manner. We have designed a new class of scheduling disciplines specifically for sharing multiple resource types in cloud datacenters. This new design allocates resources to applications by scheduling their computing tasks onto datacenter nodes. I will then focus on the problem that an increasing number of datacenter jobs specify placement constraints and can only run on a particular class of machines that meet specific hardware/software requirements (e.g., GPUs). Our recent research shows that directly extending existing policies to constrained jobs either compromises isolation guarantees or allows users to gain more resources by deceiving the scheduler. It remains unclear how multiresource fair sharing is to be defined and achieved in the presence of placement constraints. We have designed a new sharing policy, called task share fairness (TSF), to provide provable isolation guarantees and to be strategy-proof against gaming the allocation policy. Challenges remain in real-world implementations.

IQUA.ECE.TORONTO.EDU

On Data Parallelism of Erasure Coding in Distributed Storage Systems

Employed in various distributed storage systems, erasure coding has demonstrated its advantages of low storage

overhead and high failure tolerance. Typically in an erasure-coded distributed storage system, systematic MDS codes are chosen since the optimal storage overhead can be achieved and meanwhile data can be read directly without decoding operations. However, data parallelism of existing MDS codes is limited, because we can only read data from some specific servers in parallel without decoding operations. In this project, we wish to propose new coding techniques that are designed to allow data to be read from an arbitrary number of servers in parallel without decoding, while preserving the optimal storage overhead of MDS codes.

Privacy-Preserving Inference in Crowdsourcing Systems

Machine learning has widely been used in crowdsourcing systems to analyze the behaviour of their mobile users. However, it naturally raises privacy concerns, as personal data need to be collected and analyzed in the cloud, and results need to be sent back to the users to improve their local estimates. In this project, we focus on the use of a specific type of learning algorithm, called maximum a posteriori (MAP) inference, in crowdsourcing systems, and use a crowdsourced localization system as an example. With MAP inference, the accuracy of private estimates of each user in a crowd-sourcing system may be improved by analyzing estimates of other users. Naturally, the privacy of such estimates from each user needs to be preserved. Within the general framework of differential privacy, we show how private user data can be perturbed while preserving the distance between such data, so that data privacy can be preserved while producing statistically accurate learning results. Our proposed work is not limited to localization, and can be applied to other learning algorithms that use Euclidean distances between data points as their metrics.

Scheduling Jobs across Geographically Distributed Datacenters

It has become routine for large volumes of data to be generated, stored, and processed across geographically distributed datacenters. To run a single data analytic job on such geographically distributed data, recent research proposed to distribute its tasks across datacenters, considering both data locality and network bandwidth across datacenters. However, a problem remains where multiple data analytic jobs need to fairly share the resources at these geo-distributed datacenters. In this project, we focus on the problem of assigning tasks belonging to multiple jobs across datacenters, with the specific objective of achieving fairness across jobs sharing these datacenters, in terms of their job completion times.

Liang, Ben

WWW.COMM.UTORONTO.CA/~LIANG

Broadband Multimedia Communication in the Mobile Environment

Multimedia content is the single most influential factor driving the need for increased mobile network capacity and device capability. The proliferation of cloud-based content distribution services and video social-networking applications will severely stress the existing mobile systems. The inherent heterogeneity of both wireless access technologies and mobile devices enables rich and ubiquitous multimedia services, but it also significantly complicates system design. We are interested in investigations into system optimization, resource management and algorithm design to create innovative technologies for multimedia communication in the mobile environment. Promoting a synergistic approach, we work at the interface between mobile access, broadband communication and distributed-system technologies.

WWW.COMM.UTORONTO.CA/~LIANG/RESEARCH.HTML

Fair Resource Scheduling in Large-Scale Networked Systems

The principles of network science permeate wide-ranging applications such as communications, cloud computing, power grid management, transportation and biology. A central issue is how to effectively share network resources among competing agents. We are interested in developing new theories and practices for fair resource scheduling in large-scale networked systems. Examples of our investigation include cloud computing economics, distributed smart-grid control, and multiresource fair scheduling.

Heterogeneous Data Communication for Mobile Cloud Computing

Two revolutionary technologies, cloud-based computing and smart mobile devices, have fuelled the emergence of a new mobile cloud-computing paradigm. On the one hand, cloud-computing centres, accessible through the Internet, produce shared pools of always-on computing resources such as software, CPU, and storage. On the other hand, smart mobile devices have evolved, driven by the drastic rise of hardware, application, and wireless communication capabilities, to become ubiquitous tools for both content consumption and content creation. These two new technologies perfectly complement each other, with cloud servers providing the engine for computing and smart mobile devices naturally serving as human interface and untethered sensory inputs. This research targets the large-scale heterogeneous communication and networking architecture expected to serve as the backbone of the emerging mobile cloud-computing paradigm. We envisage a seamless global system of computing, communication, and applications, supported by a synergistically operated mobile cloud-computing system, incorporating hybrid macro cloud centres, micro cloudlets, and smart mobile devices. Topics of investigation include mobile computation offloading, virtual machine placement and allocation, and co-operative joint communication-computation.

WWW.COMM.UTORONTO.CA/~LIANG

Resource Management and Optimization in Wireless Networks

In next-generation heterogeneous wireless networks, the increased number of networked devices and the broadband nature of application demands will increase the need for efficient resource sharing. The goal of this research is to develop fundamental theories, communication algorithms, and networking protocols for efficient allocation of spectrum, hardware, and power in high-throughput wireless networking

environments. Topics of our investigation include co-operative communication, small-cell networks, interference management, stochastic optimization, and dynamic resource allocation.

Traffic Classification with Machine Learning and Edge Computing

With the emerging prevalence of data-hungry applications, such as augmented reality, wireless multimedia, cloud computing, and Internet of Things, the existing network infrastructure will face severe challenges in its struggle to satisfy the exploding service demands. In order to efficiently allocate the available networking resources among these diverse sets of applications, autonomous identification of the application traffic is essential for the optimal operation of a network. In this project, we apply adaptive machine learning techniques to categorize the network traffic, leveraging the availability of a vast amount of anonymous user traffic data through collaboration with a network service provider. We also take advantage of the emerging capabilities of computing at the network edge, where the network traffic is more localized with shared commonalities among local users, to improve the accuracy of traffic classification. We aim to develop practical guidelines on how to design and operate network traffic classifiers, to optimally balance the trade-off between accuracy, privacy, cost, and delay.

Lie, David

WWW.EECG.TORONTO.EDU/~LIE

Computer Systems Security

My research goal is to make computer systems safer and more reliable. With the degree to which computing has permeated our lives, from mobile smartphones to ubiquitous cloud computing, it is crucial that this infrastructure that we rely so heavily on be secure and reliable. I take a variety of approaches to achieving this goal, including techniques using operating systems, computer architecture, formal verification and networking. I like building prototypes with my students to demonstrate our ideas. My current areas of focus are building more secure smartphones and cloud computing systems.

Liebeherr, Jorg

WWW.COMM.UTORONTO.CA/~JORG

Enabling Heterogeneous Self-organizing Machine-to-Machine Networks

Machine-to-machine (M2M) communications have produced a new paradigm for creating distributed applications that connect previously unseen numbers of intelligent devices. M2M applications must satisfy demands for low cost, scalability, and low overhead, and must be able to operate over a mix of different communication systems. Thus, M2M applications can greatly benefit from self-organizing approaches to networking, because of their ability to adapt to changes of network topology, traffic mix and service requirements. However, the use of self-organizing design principles for heterogeneous M2M systems remains largely unexplored. The objective of this research project is to harvest the potential of self-organizing networks for M2M communications. The ability to have large-scale networks that can be deployed instantaneously and inexpensively creates opportunities for simpler and more resource- and cost-efficient networking, and may lay the foundation for innovative technologies. We develop new theoretical and practical approaches to realize self-organizing M2M communications in three areas: (1) scalable routing and name resolution over collections of wired and wireless networks; (2) real-time performance monitoring for network optimization; and (3) dynamically loadable and flexible traffic control algorithms for M2M networks. The project carries the proposed solutions from theory to implementation and provides proof-of-concept prototypes.

Hybrid Networks for Safety-Critical Mobile Communication Systems

Application-layer service overlay network solutions developed over the last decade have enabled the deployment of network services not natively available on the Internet, such as content delivery systems, broadcast video delivery and distributed directory services. Nodes in an ASON generally communicate in a peer-to-peer fashion without a requirement for servers or datacentres. In a collaboration with Thales Canada Transportation Solutions (TCTS), we develop service overlay network solutions in support of safety-critical communication in train control systems. Specifically, we will use service overlay networks to establish hybrid networks, where an existing (wireless and wired) infrastructure network is enhanced by a mobile SON to provide alternate communication paths. The main challenge of the project is to satisfy latency requirements of the train control system. Solutions from this project will reduce the need for infrastructure of the rail signalling system in train tunnels, as well as increase the availability of communication between train cars and the back-end infrastructure.

Liscidini, Antonio

WWW.EECG.TORONTO.EDU/~LISCIDIN

CMOS Circuits and Systems for Broadband Wireless Communication

This project will explore circuits and systems to reduce the cost and power consumption of wireless communication equipment. Low-cost flexible RF transceivers achieving low average power consumption with few, if any, external components are sought. Specifically, wireless receiver electronics that are resilient to unwanted interfering signals, and transmitters with high spectral purity will be researched. Circuits and systems amenable to implementation in CMOS will permit their integration alongside other digital signal processing with attendant reductions in cost and power consumption.

Smart Power Optimization for Wireless Transceivers

Mobile Internet access has become very popular with the introduction of 3G and 4G networks that offer high-speed wireless connections. Until now, this mobile revolution has been driven by the possibility of having low-cost mobile terminals with Internet access, enabling ICT applications in education, health, government, banking, environment monitoring and business. Although several “smarter” phones with multistandard capabilities have been introduced, the path

towards a universal mobile radio is far from smooth. Nowadays smartphones are still extremely expensive compared to simple phones and have a battery life limited to a couple of days. The main reasons for these limitations are the use of dedicated transceivers for each standard supported and the ever-increasing demand for better performance and thus faster communication. These two factors nullify all attempts to reduce power dissipation and the overall bill of material. The main idea of this project is to apply the concept of reconfigurability, which enables mobile terminals to dynamically and autonomously adapt to changing environmental conditions and reduces their energy consumption. There are many examples in nature of dynamic fitting of performance to changing boundary conditions, since it represents the best way to achieve maximum efficiency in highly complex systems. Almost all ecosystems are based on this principle, which allows them to evolve while minimizing energy dissipation.

▲ Ultra-Low-Power Transceivers for Wireless Sensor Networks

Wireless communication represents one of the most important revolutions of the last century. Although initially based only on star-mesh networks (e.g., cellular), at the end of the 1990s some wireless systems started to also adopt peer-to-peer (P2P) architectures, Wireless Sensor Networks (WSNs) being a prime example. These systems do not require base stations since they are formed by autonomous short-range wireless nodes. All these nodes monitor and control the environment defining the working area by their spatial distribution. Since the high density of units makes the system more flexible and relaxes the sensitivity of the single receiver, in ZigBee network performance is exchanged with the possibility of enabling long-lasting and cheap devices. Unfortunately the target of a large-scale diffusion of WSNs was partially missed due to difficulty in realizing both long-lasting battery life and a high level of system integration in order to minimize the costs of the single device. Recently, with a consolidation of technologies like MEMS, the possibility of energy harvesting and the evolution of compact energy storage cells, industry interest in WSNs is rising again. The goal of this project is to realize a transceiver with average power consumption below 100 uW to operate from harvested energy, sustaining an autonomous short-range communication to enable an ultra-low-power wireless sensor network. In this case low power consumption and low costs will be achieved by combining the functionality of several building blocks. Indeed, recycling bias current and devices is the prime strategy to minimize area, power consumption and complexity of the transceiver. Furthermore, minimizing the overhead associated with each start-up-wake-up cycle will maximize the efficiency of the node.

Lo, Hoi-Kwong

WWW.COMM.UTORONTO.CA/~HKLO

●● Measurement-Device-Independent Quantum Key Distribution

Quantum cryptographic systems are, in theory, unconditionally secure. In practice, quantum hacking has emerged as a key challenge to their security. To foil quantum hacking, in 2012, we (Lo, Curty and Qi) proposed an entirely new approach – measurement-device-independent quantum key distribution (MDI-QKD) – that could "short-circuit" all detector security loopholes. In other words, the system will be automatically immune to all detector side channel attacks. This is remarkable because it means that commercial QKD detection systems would no longer require any special security certifications and, in fact, they could even be manufactured by a malicious eavesdropper. MDI-QKD has attracted a lot of attention in the scientific and engineering community. We will be building a quantum communication network based on our MDI-QKD proposal and demonstrating its robustness against detector side channel attacks. We will also develop the theory of MDI-QKD and take into full account various imperfections in real-life devices. Our work will allow us to use our enemy in quantum cryptography. We are also investigating the applications of quantum communication in Smart Grids and also reconfigurable free-space networks. With the recent launch of a Chinese quantum satellite and the construction of quantum networks all over the world (Japan, China and the USA), our work is timely and important.

●● Quantum Cryptography: From Theory to Practice

We seek to build high-speed (>1 Gbit/s), unbreakable, secure communication systems based on quantum mechanics. "The human desire to keep secrets is almost as old as writing itself." With the advent of electronic businesses and electronic commerce, the importance of encryption for secure communication is growing. Standard encryption schemes are based on unproven computational assumptions. In contrast, quantum code-making offers perfect security in communication, based on the laws of physics. Our goals are to dramatically improve both the performance and the security of practical quantum key distribution systems. We do so through system building and studying hacking strategies and countermeasures.

Maggiore, Manfredi

WWW.SCG.UTORONTO.CA/~MAGGIORE

▲ Formation Control in Multivehicle Systems

This research, performed in collaboration with ECE Professor Luca Scardovi, aims at developing strategies to control rigid formations of a large class of vehicles. The vehicles in question are propelled by a thrust vector and possess an actuation mechanism that induces torques about the three body axes. Examples include quadrotor helicopters, vertical take-off and landing (VTOL) aircraft, underwater vehicles and satellites. The challenge in this research problem is that each vehicle can sense its relative displacement, orientation and velocity with respect to nearby vehicles, but doesn't know its absolute position or orientation. Yet, using this limited information, the group of vehicles should co-operate to achieve a rigid formation.

●▲ Formation Control of Nanosatellites

NASA and the European Space Agency have proposed the deployment of nanosatellite clusters to create a platform for scientific observation of the universe. The idea is to launch

nanosatellites into orbit with each satellite carrying a mirror and to assemble the cluster in a rigid formation. The result would be a large orbiting telescope with unprecedented resolution and range. One of the key challenges in deploying such a telescope is the development of formation control algorithms. The electric actuators used to propel nanosatellites (electric thrusters) produce very low thrust with low resolution. These two factors, combined with tight specifications for the accuracy of the control task, make formation control particularly difficult. This research, in collaboration with Professor Chris Damaren at UTIAS, aims at developing a formation control methodology that takes into account the characteristics of electric thrusters and solves the formation control problem with the required accuracy.

Virtual Constraints: A New Paradigm for the Control of Motion

The traditional approach to making robots perform complex motions relies on a hierarchical decomposition of the control task — motion planning at the high level and reference tracking at the low level. This approach has proven to be inadequate in complex motion-control problems such as locomotion in multilegged robots or flight in birdlike robots. This research aims at developing a new paradigm for motion control. This paradigm is based on the concept of virtual constraint—a constraint on the states of a control system that does not physically exist, but can be enforced via feedback control. The literature demonstrates that this idea has been used to induce stable walking in biped robots and we believe it can be used to emulate the flight of birds and insects and the swimming of fish and, more generally, to induce complex behaviours in robots.

Mann, Steve

METAVISION.COM

Augmented Reality Eyeglass

The Digital Eye Glass provides real-time digitization of everything you see and experience, and real-time computational mediation, augmediation, augmentation, or the like. See publications in http://www.eyetap.org/publications/ as well as the website http://metavision.com for some examples. Our metavision eyeglass is also used for teaching and research purposes. If you would like to join this project, please do one of the instructables on augmented reality: http://www.instructables.com/member/SteveMann/

Blockchain Lifeglogging: Lifelong Sensory (Audio/Video) capture

Since early childhood I've been wearing a computer system that captures my life. In the 1990s I miniaturized this into a necklace with fish-eye lens and various sensors (wearcam.org/neckcam.htm) and presented this work to Microsoft as the Keynote Address of CARPE in 2004. Microsoft has subsequently manufactured a similar product called Sense-Cam. Other companies such as DARPA, HP Labs and Nokia have also been building on this lifeglogging work. The work is known by many other names such as lifelogging, lifeblogging, CARPE, or lifestreaming. We now have a community of more than 80,000 "cyborgs" online and research continues into the mobile multimedia iPhone apps, as well as versions built inside the eye sockets of the blind. Presently we're designing a health care system bringing together health care reform, insurance reform, and distributed blockchain reputational compliance sensing. See http://mannlab.com

INTERAXON.CA

Brain-Computer-Interaction (BCI) and EEG-Based Cyborg Technologies

Brain-computer-interaction (BCI) systems developed as part of wearable computing and cyborg technologies have been widely deployed in industry. Our work was showcased at the Vancouver Olympics as part of Ontario House and continues to be adapted into various products around the world. BCI based on the Chirplet Transform (http://wearcam.org/chirplet.htm) has been the subject of a recent PhD thesis and a number of research papers. See www.eyetap.org/publications. For more on our startup company see http://wearcam.org/interaxon/ and http://interaxon.ca.

WWW.WEARCAM.ORG/COMPARAM

Comparametric Equations and High Dynamic Range (HDR) Imaging

High Dynamic Range (HDR) imaging was invented in our lab, and is now widely used, having many applications, such as in electric eyeglasses. On the pure-math side, there's the theory of comparametric equations. On the practical side, there are applications in extending the dynamic range of imaging devices such as electric eyeglasses, portable cameras and cellphones. See "Comparametric Equations with Practical Applications in Quantigraphic Image Processing," *IEEE Transactions on Image Processing*, vol. 9, no. 8, pp. 1389–1406, Aug. 2000, which you can download from www.eyetap.org/publications. Please get our attention by doing the Instructable, uploading an image, and clicking "I made it" at: http://www.instructables.com/id/HDR-EyeGlass-From-Cyborg-Welding-Helmets-to-Wearab/

WWW.EYETAP.ORG

EyeTap Electric Eyeglasses, Personal Safety Devices and Systems

The EyeTap electric eyeglasses cause the eye itself to become both a camera and a display for computer-mediated reality that achieves augmented reality but also goes beyond it, not only augmenting but also modifying. The wearable face-recognizer puts virtual name tags on people, etc. The mediated vision helps people see better and find their way better, and generally improves their personal safety. HDR (High Dynamic Range) overlays augment dark regions of the scene and diminish bright areas, and makes overlaid content easier to read. See www.eyetap.org

WWW.SPLASHTONES.COM

Musical Instruments and Other Human–Machine Interface Inventions

This research looks at innovative human–machine interaction based on arrays of air jets, or the like, to create volumetric tactile input devices such as air typing, in which the fingers move through space and interact with air currents. We've also developed a computer keyboard that has no moving parts. In place of each key is a finger hole, supplied by a system that detects restrictometric parameters of air flow of waste air from the CPU fan. The research is based on Karman Vortex shedding across bluff bodies, like the shedder bars in the hydraulophone (underwater pipe organ) and turbulences as a form of input and output medium. This research goes beyond what's possible with the hydraulophone; take a look at this video and then imagine the possibilities when we miniaturize it and use air instead of water: vimeo.com/14018088. See also our website, http://splashtones.com

WEARCAM.ORG/PAR/

Phenomenological Augmented Reality

This is the original wearable AR (Augmented Reality) invented by S. Mann in 1978, 40 years ago, to see radio waves and sound waves. Presently we are implementing this through miniaturized wearable computer systems that overlay physical world sensory content on reality. This can be used for a wide range of applications from teaching and research to everyday life. For an historical perspective, see http://wearcam.org/par/. For more on our AR eyeglass product, see also http://metavision.com

WEARCAM.ORG/MANNFIT.PDF

Physical Fitness through Integral Kinesiology

Traditional physical fitness is based on "kinematics," which is the study of distance and its time derivatives. We have a new invention, integral kinesiology, which looks also at distance and its time integrals. So rather than only considering distance, speed, acceleration, jerk, jounce, etc., we also consider absement. https://en.wikipedia.org/wiki/Absement This represents a new breakthrough in physical fitness. Absement-based training devices and apps develop the capacity to have simultaneous strength and dexterity. See research paper in http://wearcam.org/mannfit.pdf

WWW.WEARCAM.ORG/ABSEMENT/EXAMPLES.HTM

Physics-Based Modelling Using Presement and Absement

Velocity is the time-derivative of position or displacement; differentiating once more gives acceleration. But what happens when you take the time-integral of displacement? The result is something called absement. Integrating again gives absity. Integrating once more gives abseleration. Absement, absity and abseleration arise in fluid flows. For example, the amount of water flowing through a valve is the absement of how open the valve is, i.e., the time-integral of the openness. Other examples of absement arise in hydraulophonic sound production (sound from vibrations in water): see www.wearcam.org/absement/

WWW.EYETAP.ORG/RESEARCH/MEDR.HTML

Virtual Reality, Augmented Reality, Mediated Reality, and, Most Importantly, Real Reality

Augmented reality, whether through hand-held iPhone applications developed in our lab and elsewhere, or by eyePhone (electric eyeglasses), has been shown to be problematic because it causes information overload. What we've learned is that an older concept called "mediated reality" overcomes these problems and works much better. We've developed various mediated-reality iPhone apps as well as eyeglass apps, etc., that help people see better and find their way better. This work emphasizes the fundamentals of physics, computer science and engineering. It is also closely coupled with the undergraduate and graduate course ECE516: wearcam.org/ece516/. See http://wearcam.org/kineveillance.pdf and http://www.eyetap.org/papers/docs/HumanisticComputing_Mann1998_ProcIEEE.pdf and http://mannlab.com

Mojahedi, Mo

WWW.MOGROUP.UTORONTO.CA

Engineering the Electric and Magnetic Dispersive Responses of Artificial Media

Many of our modern conveniences are the consequence of our ability to control and modify the behaviour of naturally occurring materials and to design and manufacture artificial materials and systems with novel properties. In electromagnetic theory, the behaviours of materials and systems are characterized according to the so-called "dispersive effects." Depending on the researcher's area of interest and expertise, he or she may use different terminologies such as delays, indices or velocities to characterize the same dispersive effects. Despite these different nomenclatures, fundamental and important relations exist among the various delays, indices and velocities. The dispersion engineering paradigm formulates our attempts to control and manipulate these various delays, indices or velocities – the dispersive effects – by synthesizing artificial materials and designing novel systems. These systems in turn allow us to control and manipulate the amplitude and phase of voltage or current waveforms and/or electromagnetic pulses in order to achieve a desired outcome. For example, the paradigm of dispersion engineering has been used to demonstrate unusual behaviours such as negative or superluminal group delays and negative refractions. In addition to scientific interest in such unusual behaviours, dispersion engineering has been used to design more functional microwave devices such as broadband phase shifters, efficient antenna arrays and interconnects with reduced latency, to name a few.

Nanoplasmonic and Nanophotonic Devices

Performance of computers is expected to eventually reach its fundamental limits in terms of speed, bandwidth, power consumption and electromagnetic interference. The problem lies partly in the degrading performance of electrical interconnects. Unlike transistors, in which functionality increases with miniaturization, the functionality of electrical interconnects degrades substantially with miniaturization. One suggestion is to replace the electrical interconnects with optical interconnects, which do not suffer from signal latency, limited bandwidth or high power consumption compared to their electrical counterparts. However, there is a major problem with optical interconnects and waveguides. The optical mode size, and hence the device size, are approximately proportional to the operational wavelength. In other words, while transistors with dimensions of approximately 50 nm are common today, the micron size of optical devices makes their integration with electronics difficult. Surface plasmon polaritons (SPPs) – surface waves at the interface between a metal and dielectric – may provide a solution. These plasmonic waveguides, like optical interconnects, have small latency and large bandwidth but, unlike the optical interconnects, they can easily be miniaturized. However, plasmonic waveguides have their own challenges. Chief among these are (1) large propagation losses, and (2) lack of various efficient and integrated plasmonic devices such as polarizers, directional couplers and bends, to name a few. In order to overcome the losses associated with SPP while maintaining a small device size, our group was among the first to propose a hybrid plasmonic waveguide (HPWG). The HPWG can be viewed as an optimized structure exhibiting a compromise between loss and mode size. Moreover, fabrication of our HPWG is compatible with the existing silicon technology. Our HPWG can be used as a building block for the next-generation plasmonic devices such as TM- and TE-pass polarizers, polarization independent couplers and other novel components.

Moshovos, Andreas

WWW.EECG.TORONTO.EDU/~MOSHOVOS

Co-Designing Hardware and Software for Analytics

We are developing systems that can deliver real-time transactions and data analytics. By rethinking software and hardware we are exposing bottlenecks in conventional implementations boosting performance and energy efficiency and, for this reason, utility and application sophistication. We are analyzing SPARK's implementation of various analytics algorithms. This is a joint project with Professor Nick Koudas of the Department of Computer Science.

Digital Imaging Accelerators

We are characterizing digital imaging applications and developing specialized yet programmable hardware that boosts performance and energy efficiency. Our first accelerator makes possible for the first time high-end denoising (Bm3D) for high-resolution images and in real-time for HD frames.

Machine Learning Accelerators

Deep Learning is the state-of-the-art approach for many tasks such as automatically identifying image content or interpreting speech. We are developing hardware engines that offer best-in-class performance and energy efficiency for such machine-learning algorithms targeted at mobile and data centre applications. We have developed accelerators that exploit value-based properties and that can be up to nine times faster than state-of-the-art designs. Our designs do not require any changes to the underlying networks.

Nachman, Adrian

MRI-Based Impedance Imaging

This ongoing project seeks to image electric properties of tissue with novel use of Magnetic Resonance Imaging apparatus. It is joint research with Professor Mike Joy's laboratory, where Current Density Imaging was first invented. Recent progress includes the first electric conductivity images of the heart in live animals and the first method of imaging anisotropic conductivities (such as those in muscles and brain tissue).

Spatio-temporal Analysis of Multicontact Nerve Cuff Recordings

This project, in collaboration with Professor José Zarrifa's laboratory at the Toronto Rehabilitation Institute, seeks to find new inverse problem approaches for extracting information from peripheral nerves. Applications include neuroprostheses for individuals with neurological injuries and amputations, as well as a valuable tool for basic neuroscience research.

Najm, Farid

WWW.EECG.UTORONTO.CA/~NAJM

Power Grid Verification

With increased power dissipation and reduced supply voltage, modern large microprocessor chips draw over 150 amperes from the external supply! These levels of current are unprecedented in microelectronics and are a key challenge for design. Apart from the design issues of delivering a well-regulated low-voltage supply at such high current, a key problem for chip designers is to make sure that the increased voltage drop and/or rise (due to IR-drop and/or Ldi/dt drop) in the on-chip power/ground grid does not lead to functional failures. Another major problem is designing the grid so that the grid metal branches do not suffer from electromigration failures. We are aware of at least two industrial instances, (a DSP core and a large microprocessor) where the chip had to be redesigned because functional failures on silicon were caused by current-induced noise on the power grid. However, checking the grid node voltages and branch currents is very time-consuming and expensive, so that it is often done incompletely or not at all. We are developing efficient techniques for verifying that the voltages and currents of the power/ground grid are safe and within user specifications and, if the grid is found to be unsafe, for redesigning and optimizing the grid to achieve safety.

Ng, Wai Tung

WWW.VRG.UTORONTO.CA/~NGWT

Design and Fabrication of GaN Power Transistors

Gallium nitride (GaN) power transistors promise to be the game changer for next-generation power converters. Traditional silicon-based power MOSFETs are already reaching their material limits for power conversion. Aluminum gallium nitride (AlGaN)/GaN high-electron-mobility transistors (HEMTs) with high breakdown field, high-mobility 2D electron gas (2DEG), high saturation velocity, and low intrinsic carrier density are emerging as the ideal candidate for the implementation of high-frequency (10s to 100s MHz) and high-efficiency (>90%) converters. The wide bandgap materials also allow GaN power devices to operate with a high junction temperature (>200°C), relaxing the need for expensive heat removal mechanisms. The availability of GaN on silicon substrates can further reduce the cost of fabrication by making good use of existing silicon-based manufacturing facilities. This project is focused on the development of two key enabling technologies to fully exploit the potential of integrated GaN power converters: enhancement mode metal insulator semiconductor field effect transistors (MIS-FETs) and intelligent gate driving techniques. Currently, the majority of the GaN based power transistors are depletion mode HEMTs. The normally “on” characteristics make them less favourable when robustness and fail-safe characteristics are critical. Monolithic integration of silicon-based devices and GaN devices is still not practical at this time (although GaN-on-Si technology will eventually allow the co-existence of CMOS circuits and GaN power HEMTs). As a result, there is a critical need to develop novel methods/structures to implement true enhancement mode GaN power devices with silicon processing compatibility. The development of enhancement mode GaN power transistors will involve the investigation of suitable gate insulators and device structures, passivation techniques and silicon-compatible ohmic contacts. In order to take advantage of the inherent switching speed of the GaN power devices to implement integrated power converters with fast transient response, high efficiency, and compact form factor, dedicated gate driving techniques are essential. The rapid switching will produce ringing oscillation, leading to unwanted power losses (reduced efficiency) and electromagnetic interference (EMI). The second theme of this project encompasses the design of intelligent gate driver ICs to provide precision control of the gate voltage to suppress these issues.

Smart Power Integration and Semiconductor Devices

Our research group is focusing on the integration of power devices, smart-power integrated circuits and power management systems. Our group has worked extensively in the development of CMOS-compatible HV fabrication processes for automotive and consumer applications. We also have ongoing collaborative projects with our industrial research partners to develop discrete and integrated power devices, including power MOSFETs, IGBTs, and GaN power HEMTs. In recent years, we have focused on the design and implementation of VLSI power management circuits with special focus on integrated DC-DC converters with digital control. We have demonstrated the world’s first integrated DC-DC converter with dynamically adjustable power transistor sizing to optimize the power conversion efficiency at ISPSD’06. In 2010, we demonstrated a superjunction power FinFET at IEDM 2010 for the first time. This is exciting work toward enabling the next-generation FINFET CMOS fabrication technology to be compatible with the implementation of smart power ICs. Recently, we have also demonstrated all-digital on-chip temperature sensors for thermal management applications, gate driver circuits with dynamically adjustable driving strength for EMI suppression and efficiency enhancement, and dead-time control circuits. Currently, our group is working on the integration of the controller and gate driver circuits with current sensing for various power output stages. We also have ongoing work on the design and fabrication of GaN power transistors as well as their applications in power converters and class-D power amplifiers. Finally, we have just started an exciting project with Dana Canada on liquid-cooled IGBT modules for electric vehicle applications.

Pavel, Lacra

WWW.CONTROL.TORONTO.EDU/~PAVEL/

Algorithms for Learning in Networked Games with Side Information

We are working on extending Nash’s theory of games to networks. There are many applications where the game/environment is unknown; the most an agent can know is his realized payoff (or reward) as a result of some action taken. In this minimal information setting, learning refers to agents estimating the functional dependency of his payoff, based on his realized payoff. Such learning is called Reinforcement Learning or model-free learning. This minimal information setting is the most difficult case to tackle in a multi-agent game setup. Model-free learning such as Q-learning has been shown to converge only in some special classes of games, e.g., potential games. Moreover, in networked applications such as energy-aware sensor networks, there exists a separation between local and global effects on the payoff for each agent. In such applications, local knowledge about the payoff structure between neighbouring agents and neighbouring agents’ strategies may be available, whereas global information isn’t. Our goal is to design algorithms that exploit the known local information to improve the convergence rates and hopefully extend the convergence classes.

Decentralized Optimization and Game Theory

We are working on decentralized dynamic optimization from mathematical problem formulation to algorithm design. The optimizing agents could be nodes in a network, channels in a link or network or even autonomous robots in a group formation. We consider either a game theoretical framework or an optimization framework. In a game theoretical framework, agents or players are endowed with an individual cost function to be optimized and the aim is to achieve a Nash equilibrium, whereby no player has an incentive to deviate from its action. In an optimization framework, our work considers a number of agents that co-operate to estimate the minimum of the sum of their locally known cost functions. These agents are to dynamically adjust their actions, in response to their individual cost and the analogous decisions made by neighbouring agents (nodes), a consensus-based idea.

Phang, Khoman

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Friends of Design

Friends of Design is a network to promote communication within the ECE department at the University of Toronto. Our goal is to have contacts in each area of ECE willing to direct inquiries to appropriate experts within the department and the network. Inquiries are welcome from students, faculty and staff, as well as undergraduate students, outside faculty, academe, industry and alumni. Find us on Facebook at https://www.facebook.com/groups/266464955455/

Plataniotis, Konstantinos N. (Kostas)

WWW.DSP.UTORONTO.CA

Affective Signal Processing: Unravelling the Mystery of Emotions

Emotion plays an important role in our daily activities and greatly influences many areas, such as learning, decision making and interaction with others. Our decisions and courses of action are adapted according to the emotional cues we receive while interacting with others. This allows the exchange of information to be much smoother and more effective. Integrating the emotional states of a user into a human–mobile interface will provide a user-centric experience that enables the interaction to be more intuitive, flexible and efficient. We are proposing an affective signal processing system that enables real-time analysis, tagging and inference of cognitive-affective mental states from facial video and EEG recordings. This framework combines vision-based processing of the face (e.g., a frown or smile) with EEG predictions of mental states (e.g., interest or confusion) to interpret the meaning underlying EEG and facial signals over time.

Digital Pathology: Fast and Reliable Image Analysis Software

In collaboration with Huron Digital Pathology Inc., located in Waterloo, Ontario, the University of Toronto team aims to develop an innovative image processing algorithmic framework for digital pathology (DP) scanners in tissue imaging applications. Using tools from signal and image processing, computer vision, and machine learning, we plan to research, develop, and test new, cutting-edge algorithms to acquire, analyze, and store histo-pathological images. The proposed framework will greatly decrease the time and computational complexity of the image acquisition and scanning process while improving accuracy and reliability, and enhancing the end-user experience.

eDREAMs: enhancing Driver inteRaction with digital mEdiA through cognitive Monitoring

Recent advances in digital media systems have resulted in a growing interest in the use of in-vehicle digital interactive systems over the past decade, which in turn has led to serious concerns regarding drivers' safety. The eDream project aims to develop smart interactive devices that take into account the driver's cognitive state as well as the vehicle's conditions to (i) quantify and monitor the driver's workload and arousal level, and (ii) provide the driver with adaptive feedback that will mitigate the risks associated with the particular level of workload the driver is experiencing. eDream ultimately aims to pave the way for developing an advanced human–computer interaction system that (a) provides proactive and seamless support in daily life situations, (b) utilizes smart sensors, multimodality, and data aggregation to enable services that enhance the way to use technology, and (c) models user behaviour, detects changes in context and adapts accordingly to achieve proactivity.

Opportunistic Mesh Networks for Smart Home Applications

This project contributes to the advancement of the state of the art in smart home infrastructure by addressing challenges often hampering the successful implementations of ambient intelligence solutions. The primary focus of this initiative is to provide seamless integration of sensors and actuators by utilizing an OMESH-based wireless mesh network. The project aims to develop a distributed information system which will collect data from low-cost sensors, utilize artificial intelligence and multimedia algorithms to extract information, and drive a servicing robotic assistant. The output of this project will be a smart home prototype configuration, and a software module which, along with the hardware set up, will allow for replication and expansion of the results.

Poon, Joyce

WWW.PHOTON.UTORONTO.CA

Implantable Nanophotonic Brain Probes

We are developing implantable nanophotonic neuroprobes and optical systems for ultrahigh resolution, massively parallel brain activity mapping. The probes are fabricated using advanced silicon photonic and MEMS processes. The research is carried out in collaboration with California Institute of Technology, Advanced Micro Foundry (Singapore), Krembil Brain Institute, and SickKids Research Institute. We are part of the Neurotech Alliance, which seeks to advance and deploy open-source nanotechnology-enabled neurotech systems.

Integrated Photonics for Communications, Computing, and Metrology

We specialize in integrated photonic devices and circuits for communications, computing, and metrology. We work with semiconductor foundries worldwide to define new integrated photonic technologies and platforms. We are particularly interested in multilevel and multimaterial 3D integrated photonics on silicon.

Max Planck Society–U of Toronto Collaboration

Our research activities will be done in collaboration with the Max Planck Institute (MPI) of Microstructure Physics in Halle, Germany, where Prof. Poon has been appointed a Director. The research at MPI-Halle is being refocused to materials,

devices, and systems for beyond CMOS and future computing paradigms. Topics of interest in the Poon Department include devices incorporating phase-change materials, nanotechnology-enabled brain interfaces, and visible light integrated photonics for display and imaging. Prof. Poon is maintaining an academic appointment and labs at U of T. Research collaborations and joint graduate student training opportunities between U of T and the Max Planck Society are being developed.

Prodic, Aleksandar

WWW.ECE.UTORONTO.CA/PEOPLE/PRODIC-A

Power Management and Integrated Switch-Mode Power Supplies

Low-to-medium switch-mode power supplies (SMPSs), used in cellphones, computer systems, communications, vehicles, medical devices and other applications that consume power from a fraction of a watt to several kilowatts, have traditionally been controlled by analog means. This is mostly due to operation at high switching frequencies and requirements for low-power cost-effective implementation. As such, they suffer from limited flexibility and are not best suited for integration with modern digital systems. Our research has developed enabling technologies for implementing digital controllers in high-frequency low-power SMPSs and is currently focusing on fully utilizing the digital control advantages as well as on the development of novel converter topologies.

Qian, Li

WWW.ECF.UTORONTO.CA/~QIANLI

Fibre-Optic Sensing

We utilize photonics technology to create instrumentation for fibre-optic sensing and metrology. Our frequency-shifted interferometry technique has been demonstrated to have a variety of applications, such as dispersion measurement; fibre length measurements; multipoint optic sensing for stress and/or temperature sensing (used in civil structures); multipoint chemical gas sensing for environmental monitoring as well as industrial monitoring in hazardous environments; and liquid level sensing in cryogenic environments (required in space applications). We are currently extending this technique to vibration sensing. Another technology we developed is called virtual-reference interferometry (VRI). It was developed by one of our graduate students, and has been commercialized by a successful start-up company. It is used to characterize the dispersion of optical fibres, waveguides, and devices.

Nonlinear Optical Devices: Ultrafast Switching and Frequency Conversion

Many photonic devices rely on nonlinear optical properties of materials. For example, ultrafast switching devices that operate in the 100-GHz range and beyond utilize the ultrafast nonlinearity of optical materials. They can be widely used in high-speed data communication and signal processing. We are developing a sophisticated model for nonlinear optical materials that possess ultrafast and resonant optical nonlinearity and will use the model for the design of compact, ultrafast, optical logic gates for signal processing. Nonlinear optical devices are also used for frequency conversion, which has wide applications in lasers and optical communications. We are developing fibre-based frequency converters that would create new types of lasers in the wavelength region (mid IR) that is difficult to access by conventional means. Such lasers may be used for environmental sensing and biomedical applications.

Quantum Optics and Quantum Communication

Quantum physics introduces revolutionary ideas that enable the creation of new tools and methods unimaginable previously. For example, in communication, quantum technology offers unbreakable communication security. Transforming fundamental quantum concepts into practical tools is, however, not without considerable challenges. We are developing advanced engineering tools, devices and systems that utilize quantum concepts and implement them using our group's fibre-optic technologies. These include fibre-based entangled photon pair sources and fibre-based quantum key distribution systems. Our entangled photon source based on a periodically poled optical fibre is the world's simplest polarization-entangled photon pair source, and we are the first to use such a technology. It provides pure (>1000:1 signal-to-noise ratio), broadband (>100 nm), highly polarization-entangled (>99% interference visibility) photon pairs. Such sources are being used for reconfigurable multi-user quantum key distribution systems. We will further explore the technology's potential in quantum sensing.

Rose, Jonathan

HTTP://WWW.EECG.TORONTO.EDU/~JAYAR/SOFTWARE/GENIE/

Automatic Interconnect Synthesis and Optimization for FPGAs

The circuitry that connects computing modules on Field-Programmable Gate Arrays has become more complex, and the creation of it is one of the slowest and most difficult parts of digital circuit design on FPGAs. The goal of this project is to make all forms of interconnect design easier to do – we will do this by automating the creation of interconnect, and making it easier to change the connectivity. Ultimately, we wish to optimize the interconnect demands of an application circuit simply by responding to higher-level performance requirements on each logical link, such as bandwidth and latency constraints. We have demonstrated the use of a new tool, called GENIE, that can help designers make efficient interconnect at the fine-grain level (within an IP core) and at the coarse-grain level (between IP cores).

WWW.EECG.UTORONTO.CA/~JAYAR/CIMSAH/RESEARCH-PROJECTS.HTML

Eye Tracking on Mobile Devices

The goal of this project is to bring low-cost and low-energy eye-gaze estimation to mobile devices. The technology, based on Professor Moshe Eizenman's many years of experience in eye-gaze estimation, will allow tablets and phones to know where on the screen a person is looking. This project has an immense number of applications in psychiatry, education and commerce.

Machine Learning and Software to Aid in Smoking Cessation

The Ontario government spends a significant amount of money on funding smoking cessation clinics, to help people stop smoking. They do this because every dollar spent here saves two dollars by preventing the illnesses related to smoking. The Nicotine Dependence Clinic on College Street (just south of U of T) has been helping people quit smoking for many years, and does research on the subject of how to do this best. Our collaboration with that clinic (Dr. Peter Selby and his research team) has two thrusts: the first is building and validating a mobile application that will help people quit smoking — by recording their habits, reminding them of the reasons to quit, and perhaps alerting them to imminent trigger situations. The second thrust is to build a "chatbot" (a program that talks to people through texting apps, or ultimately speech) that helps smokers come to the decision to quit.

WWW.EECG.UTORONTO.CA/~JAYAR/CAM/

Smartphone-Based Diagnosis of Social Anxiety

Social anxiety disorder is one of the most prevalent mental health disorders, yet it is treatable. The goal of this research project is to develop a reliable and objective measure of social anxiety using data passively collected from a patient's smartphone. The standard approach for subjects seeking treatment for social anxiety is to receive the care of a clinician. The clinician extracts knowledge of the patient's activities and emotions, among many other attributes, from the patient themself, either verbally or through written self-report scales and questionnaires. Subjects can be unwilling or unable to give accurate accounts of their life in between visits to clinicians, and questionnaire fatigue may also arise after completing a long series of self-report questionnaires. A measure of social anxiety that is objective, consistent, and requires no input from the patient would address this problem, and that is the goal of this research project.

Sargent, Edward

WWW.LIGHT.UTORONTO.CA

Low-Cost High-Efficiency Photovoltaics

We seek to create low-cost high-efficiency solar cells. Our approach employs colloidal quantum dots – semiconductors that are synthesized and processed in the solution phase and that, through quantum size-effect tuning, allow the sun's full spectrum to be absorbed. We are also exploring new materials including perovskites, promising optoelectronic materials that exhibit impressive photovoltaic performance. Finally, we are studying systems of quantum dots embedded into perovskites, and these exhibit remarkable optoelectronic properties traceable to their atom-scale crystalline alignment.

On-Chip Gene and Protein Analysis of Cells and Bacteria

We create integrated circuits for the detection of panels of biomarkers (nucleic acids, proteins, and small molecules) that indicate the early onset of specific types of disease. We have also recently developed the means to capture rare cells, such as circulating tumour cells, on an integrated circuit, enabling subsequent biomolecular analysis. We configure nanostructured electrodes on a conventional integrated circuit; functionalize these electrodes with a nucleic acid probe having a sequence complementary to the target molecules of interest; and sensitively detect hybridization when it occurs. We are applying the chip to the early detection of cancer and to the sensitive and rapid detection of "superbugs" such as MRSA at the point of need.

Quantum Dots and Perovskites for Light Emission Applications

We develop new efficient light emitters that reduce energy consumption and achieve improved colour purity relative to existing display and projection light sources. We use colloidal quantum dots and also perovskites engineered to provide narrow light emission in the green, red, blue, and IR.

Renewable Fuels

Our investigations focus on converting solar energy into stored chemical energy, mimicking the natural photosynthesis process. We develop highly active catalysts for the splitting of water to hydrogen and for the reduction of CO^2 to carbon-based products (CO, methane, methanol) through electro-chemical processes using electricity from solar photovoltaic cells. The ultimate aims of our projects are to generate renewable fuels that help to close the carbon cycle.

Sarris, Costas

WWW.WAVES.UTORONTO.CA/PROF/SARRIS

Advanced Radio Propagation Modelling for Next-Generation Rail Signalling Systems

The public need for rail transportation safety can be effectively served by precise train control systems, enabled by advances in wireless technologies. Communications-based train control (CBTC) systems aim to provide reliable, wireless rail signalling and train navigation via a number of access points (transponders), which cover the entire area of the railway network. A critical safety mission of CBTC system planning and installation is to ensure that the number and position of access points will maintain wireless connectivity for the trains. While lack of coverage in a cellular communication network may result in dropped calls or slow data speeds, a similar effect in a CBTC system may have much more serious consequences for passenger safety. As a result, a detailed radio survey, whereby wireless propagation measurements are carried out over the entire railway network, precedes the installation of CBTC systems. Conducting a radio survey requires significant resources (time put in by qualified personnel, and funds), while the line remains out of service. Often, the pressure to complete the survey results in overestimating the necessary number of access points. This redundancy results in higher installation and maintenance costs that reduce the competitiveness of CBTC solutions. This project is focused on the development of a powerful software package that can significantly accelerate

the radio survey, using advanced propagation modelling techniques to optimize the distribution of access points for CBTC systems. The project will develop a comprehensive modelling framework for radio-wave propagation in complex railway environments, validated through measurements.

▲ An Optimization-Driven Methodology for the Design of Optically Transparent Sensors and Antennas

Touch sensors are indispensable components of the user interface of personal electronic devices such as smartphones, tablet computers and wearable health monitors. These sensors are ordinary circuits, whose usual copper wires are replaced by optically transparent (practically invisible) conductors such as Indium Tin Oxide (ITO). The use of optically transparent conductors, which suffer from higher losses compared to copper, makes the design of these circuits a challenging task. Circuit designers have by and large dealt with this challenge on a trial-and-error basis, using a combination of circuit models and electromagnetic simulations to derive topologies that trade performance for optical transparency. With the market for personal and wearable electronic devices as competitive as ever, new touch sensors are expected to support high-rate sensing of multitasking gestures with low latency. These stricter specifications test the limits of current design tools, motivating further research on the optimal performance bounds of transparent circuits and the topologies that meet those bounds under given fabrication constraints. Leveraging advances in convex optimization of electromagnetic structures and uncertainty quantification techniques, we are deriving a dictionary of building blocks for transparent circuits made with standard (ITO) and emerging (silver nanowires, graphene) materials, just as one/two-dimensional microstrip lines are for copper-based ones. In addition to touch sensors, applications of the EOTC concept to the design of transparent antennas and multifunctional touch-input/antenna surfaces are being explored.

▲●⬣ Stochastic Computational Electromagnetics

Research on computational electromagnetics has been dedicated to the simulation of arbitrarily complex yet well-defined structures. However, several cutting-edge research areas, notably plasmonics and nanotechnology, employ devices that are increasingly subject to fabrication process variability. Moreover, while electromagnetic simulators are now able to model large-scale wireless propagation problems, they are still limited by the inherent statistical variability of indoor and urban environments. In general, the development of powerful electromagnetic simulation tools that effectively incorporate statistical uncertainty is bound to have a far-reaching impact on the pace of technological advancement with respect to grand research challenges such as the design of low-cost yet efficient solar cells, the development of biomedical instrumentation for cancer detection and treatment, and wireless service planning. The current state of the art in scientific computing under stochastic uncertainty is based on post-processing data from repetitive simulations. Not surprisingly, this approach has existed for years and it is too time consuming to incorporate in a typical engineering design cycle. In other words, while the level of complexity and the significance of modelling uncertainty are constantly rising, the relevant modelling tools have remained fundamentally the same. This project is aimed at closing this gap, in order to meet the challenge of modelling statistically variable electromagnetic structures and fields with applications in plasmonics, biomedical hyperthermia and wireless communications. Our approach is focused on the fundamental reformulation of field solvers to embed statistical uncertainty in a computationally efficient manner.

Scardovi, Luca

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▲⬟ Analysis and Control of Complex Interconnected Systems

It is well recognized that control has proven to be an essential ingredient in almost every engineering system, ranging from power and automotive systems to space missions, and that feedback is a key element in many natural phenomena, ranging from molecular pathways in living organisms to ecological systems. Recent years have witnessed an increasing interest in systems that are composed of (possibly many) interconnected units. As a whole, those systems often exhibit one or more features that cannot be predicted from the properties of the individual parts. These properties (called emergent behaviour) are not an attribute of any single entity: they are irreducible and are generated by the interconnection. Emergent behaviour can lead to surprising and useful phenomena such as memory, intelligence and self-organization in cells, but can also have disastrous consequences. Examples include the spread of infectious diseases, neuronal synchronization disorders in the brain, collective motion in bacteria, and locust swarms. It is therefore of great interest to understand the principles behind the emergence of such properties and investigate methods of controlling them. The control and systems-theory paradigm is natural in this context, but unfortunately “off-the-shelf” techniques are not always appropriate for such complex systems. In the present research effort, we propose to overcome these limitations by developing new principles and methodologies that go beyond classical stability and regulation theory. Future applications range from the domain of biological networks to the domain of complex man-made systems and include closed-loop control of neuronal synchronization, analysis and control of synthetic biological circuits, and coordination in autonomous sensing networks, among others.

Sheikholeslami, Ali

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●▲⬣ High-Speed Wireline Signalling

This research targets circuit design for high-speed chip-to-chip signalling, backplane signalling and optical communication. This includes circuit designs for both the transmitter (such as the design of MUX, equalization and driver) and the receiver (such as adaptive equalization and clock and data recovery). At speeds beyond multi-Gb/s, even a few inches of a PCB trace acts like a transmission line and as such exhibits frequency-dependent attenuation, signal reflection, crosstalk, and timing jitter. The goal of circuit design in this area is to compensate for the channel attenuation, reduce signal reflec-

tions and reduce crosstalk and timing jitter so as to reduce the bit error rate (BER) of the communication link, while using less than a few mW per Gb/s operation. In the past few years, we have been able to contribute to this research through the design of ADC-based receivers that allow for extensive signal equalization in the digital domain. We have also contributed to the design of non-data-aided equalization techniques and burst-mode CDRs. Moving forward, there are still many challenges in the area of high-speed signalling as the demand for signalling speeds of 56 Gb/s and beyond grows. These data rates impose stringent requirements on both the channel equalization and the power budget for these links. We strive to address these challenges in the near future.

New Machines for Machine Learning

Machine learning has received much research attention in recent years, but the focus has always been on the "learning" part, with not much attention given to the "machine" side. So far, most of the machine learning algorithms are written for the typical von-Neumann-based computers. However, to be able to solve more complex optimization problems, these computers cannot offer the required speed, nor are they expected to in future due to the end of Moore's law. In this project, we strive to look at other, non-conventional, computer architectures, and their implementations in CMOS, in order to attain speedups a few orders of magnitude larger than those available today.

Sousa, Elvino

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Autonomous Infrastructure Wireless Networks

The research focuses on our vision for 5G wireless networks. This vision stresses the deployment aspects of the physical layer, including features that allow the physical layer to autonomously configure itself after the deployment of base stations or access points by users. The base stations and access points are deployed by users in a random manner and the network infrastructure is built and grows organically. This approach to wireless network deployment will greatly reduce the cost of base stations and access points and result in networks with much greater capacity, which is required for the emerging broadband wireless services. This research encompasses the current industry developments referred to as femtocells. The work is also related to what is referred to as cognitive radio. This research complements our two-tier vision for 5G.

Data Mining from Point Processes

This research focuses on the analysis of certain point processes with applications in data mining in the context of IoT and biomedical engineering.

Internet of Things in the Smart Home and Healthcare Environments

This research focuses on the development of sensors and analytics for application in smart home environments and healthcare.

Two-Tier 5G Wireless Networks

This project addresses a novel architecture for public cellular wireless networks. This architecture constitutes a key vision for fifth-generation wireless networks (5G). The goal of this architecture is to provide network capacities that are significantly higher than the 4G capacities and at the same time are amenable to the expected increases in traffic, not only from a higher density of users of smartphones with greater traffic demands than the current levels, but also capacity increases resulting from emerging applications such as the Internet of Things (IoT). The proposed architecture consists of a two-tier system structure where the network consists of traditional base stations and intermediary, or secondary, nodes that act as traffic aggregators. The intermediary nodes are deployed strategically in locations where traffic concentration is required, including homes, offices, vehicles, etc. Such traffic aggregators may aggregate traffic from various user terminals that are closely located or devices in machine-to-machine or IoT applications. The secondary node is designed using antennas with a relatively large number of elements and the transmission from the base stations to the secondary nodes constitutes a link that we may refer to as using the emerging massive MIMO technology. The proposed architecture will result in the links from the base stations to the secondary nodes having a very large capacity, due to the massive MIMO link. In order to design such links, novel channel estimation methodologies are required. We foresee an approach where these channel estimation methodologies make use of a database consisting of channel propagation information for different areas in a city relative to the system of base stations. The design of such a database will depend not only on topography information but also on time- and location-dependent traffic demand. In addition, other factors such as the mobility of people will come into play. Such a database will form a component of the future Smart City.

Stumm, Michael

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Software Engineering: Continuous Deployment

A small number of companies have started to implement a new way to manage the software life cycle with continuous deployment: developers produce software updates in small increments and push the updates out to production as soon as the developers think they are ready. The end result: the continuous deployment process substantially increases agility and responsiveness, and at the same time keeps developer productivity and software quality high. We did an extensive study of software development and deployment over a period of eight years at two companies: OANDA and Facebook. For example, FB deploys software out to production thousands of times a day, yet the quality of the software has only been increasing. More recently, we have been studying the development and deployment of mobile software, and were able to draw similar conclusions.

System Software Performance Optimizations

Our primary research objective is to improve the performance of large, complex computer systems (e.g., distributed systems

or multiprocessor/multicore systems). Our research approach is usually experimental: we implement systems exploiting novel technology, and we evaluate them experimentally using realistic workloads. Recently, for example, we developed a new way of doing operating system calls without requiring exceptions/traps that would allow software servers to operate significantly more efficiently. We were able to show that with this optimization, Linux Apache's throughput increased by over 100% without any modification to Apache, and MySQL's, Nginx's, and MemcacheD's throughput increased by 40%, 120%, and 35%, respectively. On two other projects, we worked extensively with Facebook on some of their back-end systems. Specifically, we developed SocialHash, which performance improves the assignment of objects to resources (e.g., assignment of HTTP requests to servers and storage sharding), and we helped optimize the performance of RocksDB, a FB-designed key-value store. SocialHash resulted in a 25% cache miss rate reduction for servicing FB HTTP requests and the optimization to storage sharding resulted in a reduction in storage access response times by 50%. RocksDB optimizes for space amplification, which reduces the amount of disk space required by 50% while increasing DB read latencies by only a marginal amount.

Tate, Joseph (Zeb)

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Energy Storage Control for Regulation and Frequency Support

With a higher penetration of solar and wind generation, there is a greater chance of large frequency excursions along with mismatches in the supply and demand of electricity. The proposed storage controller combines online system identification with model predictive control to arrest and recover from frequency excursions during major grid events (e.g., unexpected generator outages).

Grid-Connected Energy Storage Scheduling and Control

This project focuses on the scheduling and control of grid-connected energy storage to achieve multiple objectives (e.g., load balancing, frequency regulation, and prevention of under-frequency load shedding). The control design includes online parameter estimation during initial power injection along with use of model-predictive control to recover energy without the introduction of additional, unwanted disturbances.

Phasor Measurement Unit Data Characterization and Compression

Phasor measurement units (PMUs) are the primary smart-grid component being added to the North American transmission network (i.e., the high-voltage network used for large, inter-area power transfers). One of the main reasons these units are being introduced is to enable wide-area situational awareness and control of the power grid. These applications will require substantial investments in cyber-infrastructure and this research project is looking at ways to both characterize PMU data and use this characterization to achieve high levels of data compression. Results obtained thus far indicate that accounting for the unique characteristics of PMU data can lead to significantly higher lossless compression ratios in comparison to those of generic lossless compressors.

Wind Impact Metrics for Short-Term Power Grid Operations

One of the main challenges associated with the increasingly widespread introduction of wind generators is figuring out ways to control their inherent variability. While operators have always had to deal with uncertainty in electricity utilization, the availability of generation resources has traditionally been either controllable and/or known in advance. As the supply mix moves more towards variable generation resources such as wind and solar power, operators will have to learn ways to anticipate problems and take corrective actions in order to maintain system reliability. This research focuses on ways to quantify and visualize the potential impact of wind generator variability over short time horizons (e.g., four hours in the future), so that operators can better understand potential problems on the network. Because the potential impacts on the grid depend heavily on both the levels of wind generation and their distribution throughout the system, most of the work thus far has focused on developing accurate ARMAX models that account for the non-independence of wind generators' outputs. Once these models have been developed, the next stage of this project will focus on formulation and calculation of metrics that use the forecast statistics to highlight potential grid problems and suggest appropriate preventive controls.

Taylor, Joshua

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Interdependent Infrastructures

Water networks use energy for pumping, and power networks need water to cool thermal plants. Cogeneration plants simultaneously produce heat and power. Electric vehicles can both offer flexibility to, and increase the stress on, the power grid. These are just a few examples of couplings between infrastructures. This research looks at interdependent infrastructures through the lenses of control and optimization. We want to know to what extent different infrastructures can help each other by offering flexibility and reliability services, and what type of economic mechanisms best support this co-operation without constraining current business models.

Tractable Modelling of Power Electronics in Power Systems

Distributed renewable generation, energy storage like batteries and flywheels, and high-voltage direct current transmission all interface with the power grid through power electronic converters. These devices will define the character of future power systems. This research aims to develop realistic models of power electronic devices that can be integrated into system-level control and optimization routines. Examples of projects include leveraging the network structure of power systems with both AC and DC lines in control and optimization routines, and modelling the aggregate harmonics resulting from the operation of many converters in a network.

Trescases, Olivier

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Battery Management for Electric Vehicles

Despite numerous technological innovations, the proliferation of EVs in Canada is primarily limited by the range and cost of today's vehicles. Reducing the cost and extending the range of EVs are a major multidisciplinary challenge for the global automotive industry. Advances in lightweight materials, battery chemistry, battery management and power electronics are needed to meet future customer expectations and convert entire fleets from gasoline to EV technology. Another major hurdle in the widespread acceptance of EVs is the uncertainty about the lifetime and reliability of the battery pack, especially in the harsh Canadian climate. This has delayed the adoption of Lithium-Ion (Li-ion)–based battery technology until very recently, despite vastly superior energy density compared to the Ni–MH batteries used in the first generation of hybrid vehicles. Making better use of the energy capacity by increasing the system efficiency is the key to reducing the overall size and cost of the EV battery. Regenerative braking (Regen) is often used in electric vehicles to capture kinetic energy that is otherwise wasted in the brake pads when the vehicle comes to a stop. Instead of simply applying the mechanical brakes during deceleration, an EV equipped with a Regen system uses the motor as a generator in order to transform mechanical energy into stored charge in the battery. Even the latest lithium-based batteries have a relatively poor ability to quickly absorb energy without affecting long-term performance. The maximum output power of modern Li-ion batteries is typically at least three times higher than the maximum input power. Repeatedly using Li-ion batteries to both absorb this large negative power burst of Regen and provide a large positive power burst during acceleration can significantly raise the pack temperature and accelerate aging. Automotive-grade Ultracapacitors (Ucaps) have recently been developed as an energy storage technology to complement batteries. Commercial Ucaps have input and output power densities on the order of 12 kW/kg, which is at least one order of magnitude higher than that of Li-ion batteries. On the other hand, the 6 Wh/kg specific energy of these Ucaps is at least 10 times worse than that of Li-ion batteries, leading to the concept of using a hybrid storage system consisting of a smaller Li-ion battery and a Ucap. Using this approach, the battery serves purely as an energy tank, while the Ucap is sized to meet the surge input and output power requirements. Effectively managing the energy flow between the Ucap, the battery and the motor requires new power-electronic topologies and advanced control schemes. The main goal of this project is to develop new models, control schemes and power-electronic converters to extract the maximum performance from modern EV energy storage systems.

High-Frequency Digitally Controlled DC-DC Converter ICs

As the world faces unprecedented environmental challenges, energy efficiency and power management have taken centre stage. Switched-mode power supplies (SMPSs) are the key enabling technology for efficiently delivering the tightly regulated supply voltages required by today's modern mixed-signal (digital+analog) integrated circuits (ICs) and systems. The SMPS acts as the interface between the energy source, such as a battery, and the load ICs. A typical SMPS uses a combination of high-speed, low-resistance semiconductor switches, energy storage components, sensors and control circuits to regulate one or more output voltages in the presence of disturbances. State-of-the-art SMPSs have a power conversion efficiency above 90%. The resulting low heat dissipation allows multiple SMPSs to be integrated with their load circuits into a single IC. The clear trend in SMPS research is toward adaptive digital control loops, increased integration within system-on-chip (SoC) applications, higher efficiency over the full operating range and higher switching frequency, resulting in smaller energy storage components. The long-term goals of the proposed research are to make tomorrow's power management systems smaller, more efficient, more robust and more reliable, while reducing electromagnetic interference (EMI) and environmental impacts. The research focuses on new high-frequency control schemes, system-level optimization, thermal management, low-power mixed-signal circuits and power MOSFET optimization.

Power Converters for High-Efficiency LED Lighting

Electric lighting accounts for approximately 11% of the world's total power consumption. The development of cost-effective power management circuits for compact fluorescent bulbs (CFLs) has led to drastic improvements in lighting efficiency. While CFLs are clearly an improvement over archaic incandescent bulbs, they are difficult to dim, they contain poisonous mercury and the chromatic properties of the light are less than ideal. High-brightness (HB) LED modules are rapidly emerging as a promising candidate to replace CFLs in numerous lighting applications, since HB-LEDs are mercury free, scalable and can be easily dimmed. The main goal of the project is to develop smart digital switched-mode power supplies (SMPSs) to optimize the lighting efficiency and chromatic properties of HB-LED systems, using closed-loop thermal and optical feedback. The targeted controller can efficiently regulate the electrical-to-optical energy conversion process under a wide range of operating conditions.

Power Electronics for Photovoltaic Applications

Solar energy has long been recognized as one of the most abundant forms of clean renewable energy. Countless research efforts around the globe are contributing to the steady decline in the cost of photovoltaic (PV) power, with the promise of reaching grid parity in the near future. This is a complex target, as the prices of conventional energy sources are constantly in flux and heavily dependent on government subsidies. The penetration level of solar power is rapidly increasing in most developed countries because of government incentives and multidisciplinary technological advances. The exponential growth of PV technology presents tremendous opportunities for all companies in the semiconductor supply chain, ranging from discrete power devices to mixed-signal control ICs. Maximum power point tracking (MPPT) is performed on a PV array to continuously optimize the total harvested power under time-varying temperature and illumination fluctuations. It has been demonstrated that

performing distributed MPPT (DMPPT) on a per-panel or even per-cell basis, instead of using a single MPPT controller across the entire PV array, can substantially improve the total system efficiency under partial shading conditions. The main goals of this project are to quantify the benefits of DMPPT at different levels of granularity and to develop new high-efficiency power-electronic converter topologies and control schemes for both monocrystalline silicon and multijunction III–V PV systems.

Triverio, Piero

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Electromagnetic Transients in Power Distribution Networks

We develop numerical models and algorithms to predict electromagnetic transients in power distribution networks. Lightning, faults and switching activity can induce fast transients on power networks, potentially compromising grid stability. As network complexity increases, because of the penetration of renewable sources and distributed generation, predicting these phenomena becomes more and more challenging. Our techniques provide a fast way to investigate broadband transients in large power networks made by overhead, underground and submarine cables.

Modelling and Simulation of Complex Systems

Numerical techniques for the simulation of complex systems are a strategic asset in many scientific and industrial projects. However, computational complexity is often a big issue. Our group develops techniques to generate compact models for highly complex components based upon system identification and model order reduction. Models can be extracted from high-fidelity simulations or experimental results and enable a fast simulation of large-scale systems. This approach has been applied to the design of high-speed circuits and antennas.

Non-invasive Assessment of Coronary Artery Disease via Computational Fluid Dynamics

In Canada, about 1 person out of 7 dies because of coronary artery disease. Coronary arteries play a vital role, bringing oxygen-rich blood to the heart. However, lipid plaques can progressively occlude them, leading to heart failure. With graft surgery, new vessels are created to increase blood flow to the heart and prolong life. However, graft failure is quite common (for example, about 50% of vein grafts fail within 10 years). Unfortunately, we still do not know exactly why grafts fail and, consequently, how to prevent their failure. Using computational simulations guided by medical images, we are investigating how blood flows in coronary arteries after graft surgery, in order to gain new insights into the mechanisms that contribute to graft failure. Insights will then be translated into better treatment procedures, with the ultimate goal of improving patient care and reducing costs.

Signal Integrity and Electromagnetic Compatibility Engineering

Signal integrity and electromagnetic compatibility issues, like crosstalk and interference, are a major concern in the design of electronic systems. We develop efficient mathematical models, seamlessly compatible with mainstream design tools, to predict and minimize these issues from the earliest stages of design. Through our models, designers can maximize product reliability and performance without resorting to costly prototyping. This research activity is of immediate interest to the microelectronic, automotive and aerospace industry.

Truong, Kevin

APEL.IBBME.UTORONTO.CA/APEL

Computational Tools for Protein Sequences, Structures and Networks

Cells are composed of protein signalling networks that perform biological functions such as regulating cell growth or catalyzing biochemical reactions. As a result, the malfunction of proteins often causes human illnesses, such as Alzheimer's disease, heart disease and cancer. My long-term research goal is to create synthetic protein signalling networks that will allow us to one day manipulate cell biology with the same precision as we do electrical circuits and computer networks. To accomplish this goal, my proposal will focus on developing computational tools for studying protein sequences, structures and signalling networks. First, to infer the function of a protein sequence, the Smith-Waterman (SW) algorithm is used to find its similarity to proteins of known function. As sequence databases grow larger, faster sequence comparison approaches are required, such as using accelerated field-programmable gate array (FPGA) hardware. To make the FPGA solution more affordable, I will develop FPGA hardware for accelerating the SW algorithm using fewer resources while maintaining a comparable speed. The next task is to study the protein signalling kinetics within cells. Fluorescent protein biosensors are powerful tools, but the design of these biosensors often consists of trial and error. Using a computational tool to model the conformational space of protein biosensors, I improved the design, but the tool was not quantitative. To address that problem, I will include molecular factors that select preferred biosensor conformations. Last, to design synthetic protein networks or model larger existing networks, I will develop a computational tool for simulating the spatial and temporal kinetics of protein signalling networks. The sum of this work will yield insights into protein sequences and their networks that will ultimately aid in developing therapies for human illnesses.

Live Cell Imaging and Control of Caspase Kinetics Using Engineered Proteins

Over the past decade, members of the caspase family of proteases have been extensively studied for their critical role in apoptosis. The caspase family displays rich spatial and temporal kinetics in living cells, such as cascading activation and differential subcellular expression. While such characteristics confound many biosensor designs, they accentuate the strengths of fluorescent protein biosensors. By employing the principle of fluorescence resonance energy transfer (FRET),

protein biosensors can be created to image the kinetics of caspase activation in living cells. Furthermore, we can control the exact moment that caspase activation occurs within the cell using an inhibitory protein of caspase that is engineered to be switchable on [Ca^2+]. This goal will be accomplished by achieving three things: (1) targeting caspase biosensors to subcellular organelles; (2) imaging caspase cascades in living cells; and (3) finally, engineering proteins to control caspase activation based on XIAP (an X-chromosome-linked inhibitor of apoptosis protein) and a Ca^2+ binding protein called calmodulin (CaM). This work will pioneer designs for engineered proteins that will provide new tools for fundamental studies in cell biology.

Valaee, Shahrokh

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Application of Machine Learning in Medical Imaging

In collaboration with researchers from the Department of Medical Imaging at St. Michael's Hospital in Toronto, we are working on the application of Deep Neural Networks (DNNs) for medical image classification. We are particularly interested in the application of DNNs with small data, where the volume of data is not enough to properly train a DNN and/or data is unbalanced across different classes. We have investigated three approaches to address the small data problem: (i) generation of data using Generative Adversarial Networks (GANs); (ii) Resampling of data using redial transformation; and (iii) network simplification through pruning.

Localization of Wireless Terminals in Indoor Environments

Location-based services (LBSs) are emerging as new applications on mobile phones. In an LBS, the main challenge is to locate the user, especially in indoor and covered areas where GPS service is not available or has unacceptable errors. In this research we estimate the location of a mobile phone using the strength of signals arriving from Wi-Fi access points. We have designed and developed the system on three Wi-Fi–enabled phones and PDAs and have tested it in an office building at the University of Toronto, in a shopping mall in north Toronto and at the Canadian National Institute for the Blind (CNIB). The system has a tracking and navigation feature that uses voice instruction to help visually impaired individuals find their way in indoor environments.

Wireless Communications in Vehicular Environments

In 2000, an estimated 6,394,000 motor vehicle crashes were reported to the police in the U.S. Based on a series of in-depth investigations of police reports and on-scene investigations, human factors were found to be the definite cause of 70.7% of the crashes. Most of those accidents could have been prevented if devices that allowed vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) communication had been installed in cars. The goal of our research is to create vehicular ad hoc networks (VANETs) that can be used to enhance safety on roads and to provide telematic services such as information on road conditions and traffic congestion, and mapping.

Veneris, Andreas

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CAD for VLSI Verification, Debugging, Testing and Synthesis

The semiconductor industry has products reaching all parts of commercial and consumer markets domestically and internationally. The rapid growth of this industry in the past 30 years is attributed partly to advances in the Electronic Design Automation industry community and Computer-Aided Design (CAD) tools that assist engineers designing such complex high-performance devices. The research of our group centres on the development of CAD software that expedites the verification, debugging, synthesis and testing of computer chips. Our research has been funded by major government and industrial partners and has won awards at premier conferences for its impact on the community.

Voinigescu, Sorin

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56 GS/s 7-bit DAC and ADC

The research focuses on architectures and physical implementation of low-power 56-GS/s, 6-8 bit digital-to-analog and analog-to-digital convertors for next-generation optoelectronic transceivers with multilevel modulation formats. The circuits will be fabricated in the world's most advanced 55-nm SiGe BiCMOS technology and in 22-nm FDSOI Technology. An 8-bit 70-GS/s DAC with over 32-GHz analog output bandwidth and 1.2-Vpp differential output swing has already been fabricated. Two 6-bit SAR ADCs with 32-GHz analog input bandwidth and 40-60 GHz sampling clocks, based on a patent-pending architecture, have been designed and are now in the fab. A 22-nm FDSOI 6-bit ADC front end with 61 GHz analog bandwidth and 128 GS/s sampling rate has been demonstrated this year.

200 GS/s DACs and ADCs for Optical Transceivers with QAM and OFDM Modulation

As internet traffic continues to increase exponentially because of the explosion of mobile multimedia devices, there is renewed demand for electronic circuits and optoelectronic systems that can operate at serial data rates in excess of 100 Gb/s. The next generation of optical-fibre standards will inevitably imply the deployment of both higher-level modulation schemes such as 16-QAM and OFDM and of higher serial bit streams at and beyond 112 Gbaud. Optical modulators require 3–6V electronic signal swing for proper operation. The large voltage swing and the very broadband operation from DC to over 80 GHz are beyond the best performance reported for digital-to-analog converters in nanoscale CMOS and SiGe BiCMOS technologies. One option would be to use a low voltage swing DAC followed by a very large voltage-swing, large gain, broadband linear amplifier fabricated in III-V technology.

This is an expensive multichip solution. In addition, because of the relatively large resolution (7–8 bit) required, it is almost imperative that the DAC directly drive the optical modulator to avoid signal distortion. This proposal seeks to research and develop novel large swing (>3V differential), multibit (6–8 bit) 55-nm BiCMOS, 28-nm and 22-nm SOI CMOS DAC and 60-GHz bandwidth ADC topologies for 16-QAM, 64-QAM and OFDM optical transmitters operating at 1 Tb/s. Several record-breaking front-end building blocks of the ADC and DAC recently developed in our group and operating at 120 Gb/s with over 90 GHz bandwidth have been published. This year we are focusing on the implementation of the analog front end of ADCs with over 200 GHz sampling rates and 60-GHz analog bandwidth. Already, a record-breaking 128-GS/s 5-bit time-interleaved Flash ADC has been demonstrated in 55 nm SiGe BiCMOS and will be presented at the 2018 IEEE BCICTS.

▲ Low-Power mm-wave Distance Sensors and Tags

Ultra-low-power single-chip mm-wave distance sensors and active tags will be investigated and demonstrated in silicon at 60 GHz, 80 and 160 GHz. SiGe BiCMOS and SOI CMOS technologies will be used and compared for lowest power operation. The main applications are in autonomous navigation of vehicles and drones, distance measurements, and touchless gesture control of small wearable devices and IoT connected devices. This year, the research focuses on developing a new polarimetric sensor architecture at 160 GHz and on a novel 80 GHz active tag topology with IQ modulation.

▲ Quantum Computing ICs on a CMOS Platform

The goal is to study the feasibility of high-temperature (high-T) Si and SiGe electron/hole-spin qubits and qubit integrated circuits (ICs) in commercial 22 nm FDSOI CMOS technology and to explore their scalability through simulation to 2 nm dimensions, when 77-300 K operation is predicted. For the first time we report (i) integration of qubits and electronics on the same die, (ii) strained SiGe hole-spin and strained Si electron-spin FDSOI qubits on the same die, (iii) a new hardware scheme for improved fidelity, and (iv) propose a monolithic processor architecture which allows for short, 10-20 ps spin control pulses to compensate for short spin phase coherence lifetime. We also demonstrate that, at 3.3-6 K, MOSFET cascodes can be operated as qubits in the subthreshold region while behaving as classical transistors in the saturation region, suitable for mm-wave mixed-signal processing.

Wong, Willy

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⬟ Auditory Gap Detection and Clinical Implications

Auditory processing disorder affects nearly 5% of school-aged children as well as 70% of the older adult population. Such individuals will have healthy peripheral hearing but deficits in the processing ability of auditory information in the central nervous system. One reason is due to the low temporal resolution of the auditory system which leads to difficulty in perceiving speech under noisy circumstances. Hence diagnosis is extremely important as it may affect a child's ability to develop normally, and may allow schools to better tailor their teaching to the students. For older adults, an early diagnosis may provide a means for a better quality of life. We are developing new electrophysiological methods that will allow for rapid detection and diagnosis of auditory processing disorder in collaboration with Vivosonic Inc., a world-leading Canadian developer of medical devices for audiometric solutions.

⬟ Neuromodulation for Motor Movements

We are interested in studying how the different regions of the brain communicate together to co-ordinate complex motor movements like a reaching task. There are over 100 billion neurons in the brain, but how do the different networks of neurons communicate to complete a complex task? We tackle this problem both experimentally, in collaboration with neurologists and surgeons at Toronto Western Hospital, through studies on deep brain stimulation, and we also collaborate with mathematicians to develop models of synchronous neural activity which mimic the experimentally observed behaviour. We use Kuramoto oscillator models and study phase transitions in order to develop understanding of the underlying mechanism. Through furthering basic knowledge, we hope to pioneer new neuromodulation techniques which help those with restricted mobility to restore their capability for movement.

⬟ Theoretical Modelling of Sensory Processing

We develop theoretical models to understand the functioning of the senses (seeing, hearing, etc.). These models are based on a new approach involving statistical physics and information theory. The end result is a system of equations with very few adjustable parameters that is able to predict, with incomparable generality and universality, the neural response of sensory systems in all types of organisms and sensory modalities. This theory is currently used to guide the development of sensory prostheses (see the next entry).

⬟ Visual Prosthetic Devices

In collaboration with ophthalmologists in Japan, we are designing the next generation of visual prosthetic devices to restore sight in those people with retinitis pigmentosa (loss of photoreceptor cells). This new method involves implanting a photosensitive dye layer into the retinal space and using this passive, biologically compatible method to induce electrical responses in the eye, thereby triggering "vision" and allowing the person to see. The photosensitive dye is superior to other existing prosthetic devices because it does not require external cameras or arrays to be implanted into the eye. Using theory developed at the University of Toronto, we help guide the development to ensure that what the person sees is faithful to the actual scene he or she is viewing.

Wonham, Murray

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▲ Supervisory Control of Discrete-Event Systems

Our research is on supervisory control of discrete-event systems, that is, logic control of systems described in a

framework of automata and formal languages. We focus on system architecture and "intelligent" computing techniques as a means of confronting state-space explosion and exponential complexity. Specifically, architectures include monolithic (as a "worse case"), refined to decentralized, distributed, and hierarchical and their combination as heterarchical system organizations; while computing includes modelling and algorithmic development using state-tree structures, an adaptation of state charts. Existing applications by ourselves and others include manufacturing workcells, chemical engineering processes, automobile push-button systems and industrial diagnostic systems.

Yoo, Paul

HTTPS://IBBME.UTORONTO.CA/PEOPLE/CORE-FACULTY/PAUL-B-YOO/

Advancing Neural Interface Technologies

We are developing novel interfaces that are aimed at improving the clinical use of neurostimulation technologies, which include functional electrical stimulation and electrical neuromodulation. Projects include the design of (1) a minimally invasive method of electrically activating the peripheral nervous system (enhanced transcutaneous electrical nerve stimulation, eTENS), and (2) peripheral nerve electrodes that can achieve long-term recording of neural activity.

Electrical Neuromodulation for Pelvic Dysfunction

The objective of this project is to develop therapeutic platforms for treating pelvic dysfunction in individuals with neurological or idiopathic disorders. This involves (1) the investigation of neural mechanisms underlying bladder-inhibitory reflexes evoked by peripheral nerve stimulation; (2) development of minimally invasive methods of electrically activating these neural pathways; and (3) the clinical translation of these technologies in patients. Our current areas of interest include chronic clinical problems of bladder and bowel function.

Yu, Wei

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Co-operative Communications for Wireless Cellular Networks

Prof. Wei Yu's research program aims to use novel co-operative transmission techniques to enhance the capacity, coverage and reliability of wireless cellular networks. The goal is to develop novel co-ordinated signal processing, resource allocation and network optimization techniques for the design and analysis of interference management and mitigation methods for future wireless networks. Interference mitigation is expected to become a crucial task in wireless system design as future networks become more densely deployed, frequencies more aggressively reused and the network topologies increasingly heterogeneous. Prof. Wei Yu's research program focuses on two network architectures in particular: the cloud radio-access network (C-RAN) architecture where base stations co-operate in transmitting and receiving signals, and the heterogeneous architecture where remote radio units are deployed within the cellular structure to enhance coverage. This research aims to advance the state of the art in the theoretical capacity analysis of wireless networks and to impact the design philosophy, standards development and evolution of future-generation wireless networks.

Massive Device Connectivity

Massive connectivity is an important application scenario for future wireless networks in which millions of devices may be connected to the network, but with possibly sporadic traffic. The main goal of this research project is to understand the fundamental limits and to design coding strategies to support massively connected low-latency wireless random access in a cellular environment.

Ultra-Reliable Communications

Prof. Wei Yu engages in research in ultra-reliable communications for next-generation cellular networks. These new communication protocols are motivated by emerging machine-type communication scenarios where reliable and low-latency transmissions are required for sensing, control, and actuating applications.

Yuan, Ding

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JVM Performance Overhead on Big Data Analytics Systems

We are seeing a recent trend: many widely used, latency sensitive, big data analytics systems, such as Hadoop, Cassandra, Spark, etc., are built on top of Java Virtual Machine (JVM), despite debate on the overhead of doing so. This project aims to analyze the extent and causes of JVM performance overhead in the above-mentioned systems. Surprisingly, we have found recently that the warm-up overhead, i.e., class loading and interpretation of bytecode, is frequently the bottleneck. For example, even an I/O intensive, 1-GB read on HDFS spends 33% of its execution time in JVM warm-up, and Spark queries spend an average of 21 seconds in warm-up. The findings on JVM warm-up overhead reveal a contradiction between the principle of parallelization, i.e., speeding up long-running jobs by parallelizing them into short tasks, and amortizing JVM warm-up overhead through long tasks. We built HotTub, a new JVM that amortizes the warm-up overhead over the lifetime of a cluster node instead of over a single job, by reusing a pool of already warm JVMs across multiple applications, to solve this problem. The speed-up is significant. For example, using HotTub results in up to 2.38X speedups for Spark queries, despite not adhering to the JVM specification in edge cases. This result appeared in OSDI'2016, the best conference in systems software.

Non-intrusive Failure Diagnosis for Distributed Software Systems

Real software systems inevitably experience failures. When such failures occur, it is critical to diagnose them so as to bring the systems back online. However, the challenge is also daunting: the most widely used systems are built using distributed systems, where hundreds of thousands of servers work together to process user requests. When a failure occurs, one has to reconstruct the complex execution of the processing of this request across these servers to diagnose the problem. Professor Yuan pioneers the area of non-intrusive failure diagnosis. Unlike intrusive approaches, his does not require any modifications to the target systems to collect additional data, which face serious deployment hurdles in practice as vendors are often reluctant to alter their production systems. Instead, his technologies can reconstruct the (failed) software execution entirely from the system's existing log output. His research has been published in the proceedings of the best conference in systems software (OSDI) multiple times, and has been licensed by Huawei Technologies.

Simple Testing Can Prevent Most Critical Failures in Distributed Software Systems

Large, production-quality distributed software systems, as exemplified by Google.com, Facebook.com, Amazon.com, etc., still fail periodically, sometimes catastrophically where most or all users experience an outage or data loss. Conventional wisdom has it that these failures can only manifest themselves on large production clusters and are extremely difficult to prevent a priori, because these systems are designed to be fault tolerant and are well tested. This project asks a simple question: why do these systems still fail and what can be done about them? By investigating 198 user-reported failures that occurred on production-quality distributed systems, we found that almost all (92%) of the catastrophic system failures are the result of incorrect handling of non-fatal errors, and, surprisingly, many of them are caused by trivial mistakes such as error handlers that are empty or that contain expressions like "FIXME" or "TODO" in the comments. We therefore developed a simple static checker, Aspirator, capable of locating trivial bugs in error handlers; it found over 200 new bugs that have been fixed by the developers. After appearing in the best conference in the systems software field (OSDI'14), this work has had an immense impact on the software industry. Google and HBase developers will be using Aspirator. The work has been the subject of many blog entries and thousands of Twitter tweets, and has appeared twice on the front page of . *W0E‰ 9É ›* . The paper has been disseminated in the developer's email list for HBase (by its founder) and ZooKeeper. It has been discussed at numerous industrial conferences, including the Cassandra Summit (keynote by Cassandra's founder), InfoQ's QCon, RICON 2014 (keynote), Surge 2014, and is included in "Papers We Love," a developer community interested in reading and discussing computer science papers, with over 10,000 members and chapters in over 30 cities around the world. Some universities, like the University of Illinois at Chicago, have made this paper mandatory reading for their undergraduate programming class.

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Analysis and Characterization of Cloud Applications with Flash Memories

In the past, data-centre applications often found poor utilization of CPUs due to the idle wait for the slow disk-based storage systems. The rise of flash memory–based storage brings the opposite problem: the CPUs cannot keep up with the storage. This projects aims to quantify the new gap, and obtain new insights into the interaction between applications, operating systems, and storage.

Channel Modelling of NAND Flash Memory

The goal of this project is to investigate physical channel characteristics of NAND flash devices to extract soft information for soft-decision error control coding, in the hope of permitting flash memories to operate well beyond their ordinary service life.

Erasure Coding Acceleration

Erasure coding is a generalization of RAID that can enhance the reliability and availability of peta-byte scale storage systems. One problem that prevents its adoption in high-performance storage systems is its computational complexity, which commands a large amount of CPU cycles. The project aims to find efficient acceleration hardware built on FPGAs.

Performance Modelling of Garbage Collection Algorithms

A central concern of flash memory is its limited number of cycles; a flash memory cell can be erased/written as it directly relates to the service life of flash-based storage. Another nuance flash-based storage has to address is that there is no in-place update as in traditional disk drives. Garbage collection (GC) therefore has to be used. The key performance metric of GC is write amplification, or the amount of non-productive write. The goal of this project is to establish a parametric analytical model of realistic garbage collection algorithms, such that write amplification can not only be predicted based on design parameters and workload characteristics, but also be provisioned to deliver the best result.