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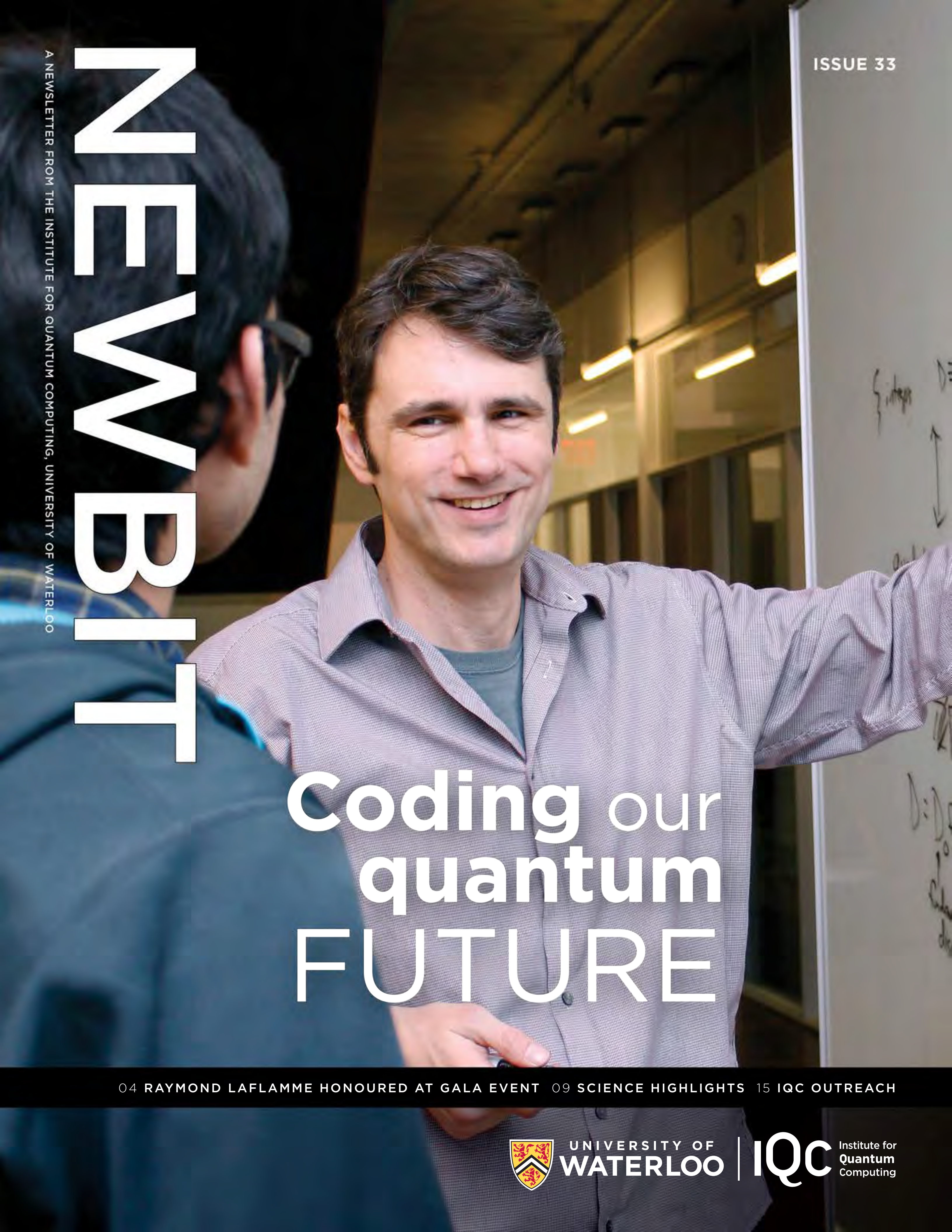


Coding our quantum FUTURE

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

FEATURE ARTICLE

Coding our quantum FUTURE

The math that drives quantum computing

Take one look into JON YARD's office, and you wouldn't be surprised to learn he's a quantum theorist. A whiteboard filled from top to bottom with complex algebra sits on the wall opposite his desk. In the corners are layers of frantic smudges from equations erased, scribbled over and erased again.

IQC researcher JON YARD is a professor in the Department of Combinatorics & Optimization in the Faculty of Mathematics, and an Associate Faculty at the Perimeter Institute for Theoretical Physics.

Yard studies quantum information science. He uses ideas from physics, mathematics and computer programming to investigate the theory behind quantum systems and networks.

While other researchers work to build the physical parts of a quantum processor, Yard is looking at the problem from the top down. His goal is to figure out the capabilities and limitations of those systems for processing information.

THE NUTS AND BOLTS OF COMPUTATION

From a high level, quantum processors aren't so different from the ones we use today.

In classical computing, the basic information unit is a bit. These bits are operated on by logic gates, and a series of these gates makes up a typical circuit. If programmers want to employ this system to solve complex problems, they write step-by-step instructions called algorithms that tell the computer exactly what they want it to do.

One model for quantum computation works in much the same way. It uses quantum circuits composed of a series of quantum gates to manipulate individual qubits. Quantum algorithms then execute instructions that exploit the quantum mechanical properties of superposition and entanglement to solve problems that could be much more difficult for, or take longer on, a classical computer.

Theoretical research is often a collaborative effort. Here, **JON YARD** works on a problem with undergraduate research assistant **SANKETH MENDA.**

Determining which problems admit a quantum speedup is an important challenge.

As Yard says, "We need new quantum algorithms." Additionally, certain quantum gates appear to require enormous resources each time they are used. Minimizing the use of these gates allows longer and more reliable computations to be carried out at tremendous savings in cost. Codes for reliably implementing gates also need to be optimized, drawing on our current understanding of how quantum computers might work in practice.

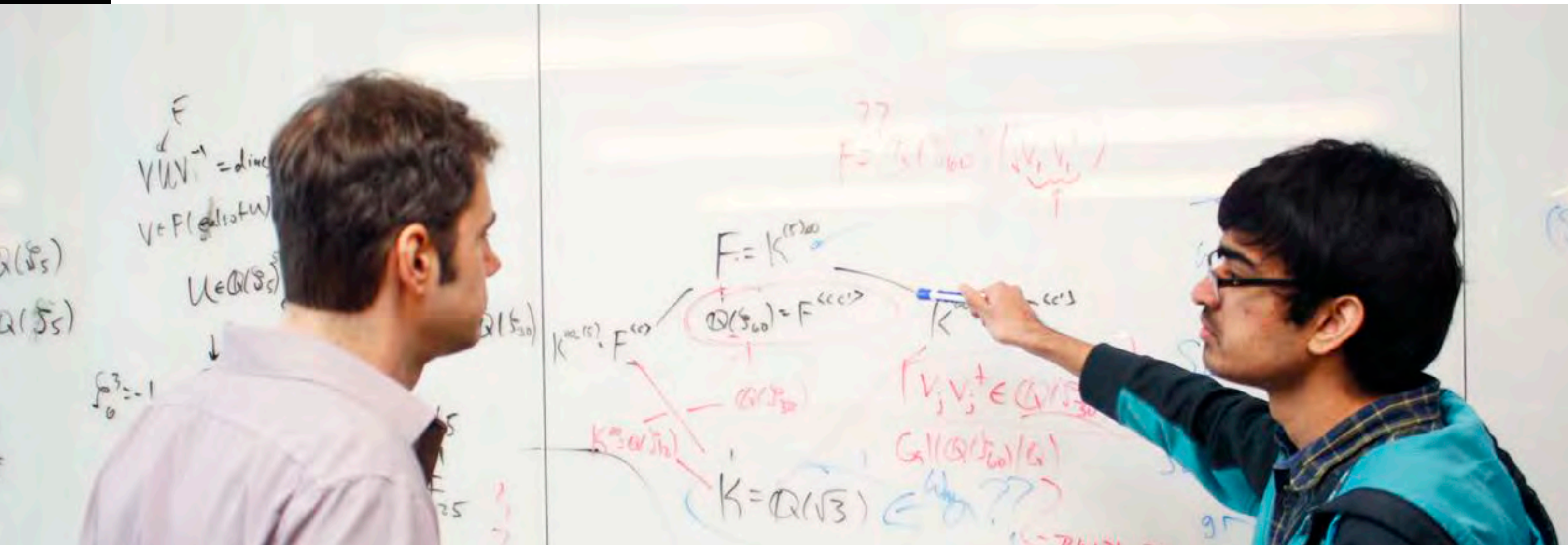
Yard is creating new compiling schemes for quantum gates and devising new error-correcting codes to ensure that quantum computers will work, despite the natural tendency for quantum information to leak into the surrounding environment.

PROBLEMS IN FAULT-TOLERANCE

Achieving fault-tolerance in classical computers is fairly simple, as they're able to employ redundancy. For example, if one or two bits in a logic gate become corrupted, the information they contain isn't lost since computers can copy and store that information multiple times.

Quantum mechanics, however, doesn't allow for the creation of identical copies. If qubits are exposed to their environment or disrupted by quantum noise, the quantum information is lost.

This presents a challenge for theorists – but not an impossible one. Yard is already able to create optimal schemes for fault-tolerant quantum gates through the "deep and subtle mathematics" of algebraic number theory. The more efficient these gates are, the fewer gates experimentalists will have to implement in the lab, saving significant resources.



JON YARD works alongside undergraduate research assistant SANKETH MENDA.

"You ask questions, and you try to answer them, and you keep asking questions... eventually you find an answer."

SMALL STEPS FORWARD

In Yard's own work, the real challenge is finding a way to merge these small-scale fault-tolerant systems into the greater whole. He can reason about large systems of multiple qubits, but the dimensions of those systems grow far too fast to reliably store all their information.

Ultimately, the process of invention can take some time. As Yard says, "You can't force a breakthrough – they just happen." He doesn't often see researchers sprinting down the halls screaming "Eureka!" However, small moments of discovery still happen every day. It's that very thrill – of puzzling out the next algorithm, expanding our insight into the nature of the quantum world – that pushes Yard forward.

"We're just trying to understand things," he says. "You ask questions, and you try to answer them, and you keep asking questions... eventually you find an answer."

IMAGINING THE QUANTUM FUTURE

Moving forward, Yard plans on taking a big-picture approach to tackling quantum challenges. Certain hardware implementations for a quantum computer might work better with some algorithms and error-correcting codes over others. Uncovering these optimal combinations will enable Yard to start envisioning the system architecture for a fully-fledged quantum computer. He soon hopes to collaborate with colleagues to turn mathematical theory into experimental reality.

In the meantime, however, Yard continues to follow his curiosity. As he says, "Ideas emerge from studying theory." Every question asked sparks new discoveries and ideas. ■