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Linear Logic

A novel approach to computational logic is reaching maturity, opening up new vistas in programming languages, proof nets, and security applications.

When the French logician Jean-Yves Girard first visited Xerox PARC during a trip to Silicon Valley in 1984, he knew he was in the right place. Seeing computer scientists collaborating with linguists, ethnographers, and other non-programmers, he started to consider the possibilities of bridging computer science with his own branch of philosophy. "What impressed me most was the change of spirit," he recalls. "It was a very special time."

Following his trip to California, Girard began work on his breakthrough paper "Linear Logic," which postulated an entirely new approach to logic, one deeply informed by computational principles. In the ensuing years, the principles of linear logic have found their way into a broad range of other arenas including programming languages, proof nets, security applications, game semantics, and even quantum physics.

In the early 1980s, logicians like Girard were just starting to take an interest in computer science, while a handful of computer scientists were starting to recognize the potential of logical proof systems as a framework for functional programming. Linear logic represented an important step forward for computer science because it challenged the conceptual limitations of traditional classical logic. For thousands of years, the study of logic had hinged on the assumption of permanent Aristotelian truths, or unchanging essences. *A* was *A*, *B* was *B*, and would ever be thus. Through the lens of computer science, Girard began to see a way out of this "foundational aphoria." His chief insight was that logic could function without this unspoken assumption of perenniality. "This was a big shock," Girard recalls. "The discovery of linear logic went completely against all the things I had been taught in logic."

French logician Jean-Yves Girard, author of the seminal paper "Linear Logic."

PHOTOGRAPH BY ANNE VAN DER STEGEN

Whereas classical logic might support an assertion like type A → B, computer programs require a set of concrete instructions for transforming *A* into *B*, such as applications, variables, or exception handlers. In the eyes of a computer program, then, *A* is not a permanent entity but a consumable resource. To address this problem, Girard proposed a resource-conscious approach to logic, laying out an entirely new framework capable of describing resources that could be used and depleted during the course of an operation.

In the nearly quarter of a century since Girard published his seminal paper, most of the foundational theoretical work in linear logic has been completed. However, computer scientists continue to find new applications of the theory across a wide range of disciplines like proof nets, categorical semantics, and computer security applications.

At Carnegie Mellon University (CMU), computer science professor Frank Pfenning has been exploring the application of linear logic to distributed security problems. After one of his students introduced him to linear logic, he became convinced it provided the ideal conceptual framework for specifying difficult-to-encode rules like complex privacy policies or resource conservation strategies. "I was most interested in characterizing, logically, complex properties of distributed systems," Pfenning explains.

Working with a team of students, he used the principles of linear logic to implement a proof-carrying file system (PCFS), featuring an access control policy that is stated as a logical theory, wherein file access is granted on the condition of a logical proof of policy compliance. "Linear logic is tremendously useful here," he explains, "because we can easily represent the change of state that takes place, for example, when you read or write a file."

"The discovery of linear logic went completely against all the things I had been taught in logic," says Jean-Yves Girard.

Working with Symantec, Pfenning and CMU postdoctoral researcher Deepak Garg have applied PCFS to formalize the access control policies of the national intelligence community in the United States. In collaboration with Jamie Morgenstern, an undergraduate student from the University of Chicago, Pfenning is now working on extending the implementation to handle even more complex policies. Pfenning feels the biggest challenges lie in translating complex real-world rule sets into unambiguous logic. The ideal outcome is what he calls "an abstract logical form that is theoretically tractable and at the same time practically useful."

Proof Nets

Linear logic has also opened new doors in the field of proof nets. Prior to the introduction of linear logic, most computer scientists working in the field relied on intuitionistic logic, following the well-established Curry-Howard Correspondence, which suggested that formal proof calculi shared a common structure with computational models. Before the advent of linear logic, this model had served as the de facto standard for types. "Linear logic enriched this world greatly," says Dale Miller, director of research at INRIA Saclay, who has spent the last several years applying the principles of linear logic to proof systems.

"Originally, proof systems were used to build 'big-step' inference rules from the 'small-step' inference rules of linear logic," Miller explains. Now, he is exploring the possibilities of so-called focused proof systems by using those "small-step" inference rules to build a range of proof systems for classical and intuitionistic logic. "If one has an interpreter for focused linear logic, that interpreter can be used as an interpreter for many proof systems," says Miller, citing the examples of emulating sequent calculus and tableaux. "Different choices yield different and

Obituary

Nicolas Georganas, Multimedia Guru, Dies at 67

Nicolas D. Georganas, a leader in multimedia networking, died on July 27 at age 67. Georganas was founding editor-in-chief, in 2004, of *ACM Transactions on Multimedia Computing, Communications, and Applications* (*ACM TOMCCAP*). He promoted the linking of video, audio, and other sensory input—lately focusing on haptics—for a wide variety of distributed interactive systems, from telemedicine to high-level gaming to security.

"He is one of the godfathers of multimedia," says Ralf Steinmetz, editor-in-chief of *ACM TOMCCAP* and adjunct professor at Technical University Darmstadt. "Whatever we did in this area, particularly with ACM, he was from the beginning involved in it."

"He was incredibly kind and very friendly," says Klara Nahrstedt, a computer science professor at the University of Illinois at Urbana-Champaign, who described Georganas as an elder statesman in a young field. "He truly served many people as a mentor."

Born and educated in Athens, Greece, Georganas earned a Ph.D. in electrical engineering at the University of Ottawa, where he served on the faculty from 1970 until his death. Georganas' research contributions included ambient multimedia intelligence systems, multimedia communications, and collaborative virtual environments. He published more than 425 technical papers and is co-author of *Queueing Networks—Exact Computational Algorithms: A Unified Theory by Decomposition and Aggregation*.

Georganas was dedicated to building a multimedia community, and was known for encouraging his students, many of whom are now professors in Canada and elsewhere. Steinmetz said Georganas, who was fluent in English, French, and Greek and spoke some Spanish and German, wanted the community to have an international flavor and championed tolerance among its members. At the same time, he demanded people do their share of the work, and he'd push to get what he wanted. "He tried always to be fair," Steinmetz says. "He was also good at twisting arms."

—Neil Savage

often, known proof systems."

In recent years, linear logic has also given rise to a new genre of programming languages like Forum, Lolli, and Lygon that incorporate richer forms of expression to allow more powerful approaches to proofs.

Looking ahead, Pfenning believes there is still work to do in improving the state of automation in linear logic. "We need theorem provers, model checkers, and other tools for working with linear logic to make its application to real-world problems easier." Miller agrees that linear logic has the potential to support the automation of theorem proving. "Focused proof systems give a central role to inference rules that are invertible," he explains. "When a formula is introduced by an invertible rule, that formula can be discarded. Such information is useful in building theorem provers."

Miller also sees an opportunity to use linear logic and proof search to provide specifications of algorithms, using proof theory research to help in reasoning about such algorithmic specifications. He also hopes to see the day when a large "logic of unity" might take shape that would encompass classical, intuitionistic, and linear logic in one grand system.

Where could linear logic go from here? Other active research areas include concurrency theory, quantum computing, game semantics, implicit computational complexity, and the verification of imperative programs with heaps using separation logic, a close cousin of linear logic.

With the field maturing, the fundamental principles of linear logic are receding into the background as an area of active inquiry as computer scientists learn to apply the established principles to emerging computational problems. "Linear logic is no longer alive as a specific subject in which you work," says Girard. "It's become something classical. It is part of the toolbox."

Pfenning agrees with Girard's assessment, but thinks linear logic lacks the widespread exposure it deserves at every level of the computer science curriculum. "It should be part of the standard toolkit," he says, "but I don't think it is taught in enough places right now, especially in the United States."

Girard, meanwhile, has moved on from the problems of computing to set his sights on more esoteric quandaries. "I would like to understand why certain things are difficult, why the world is not transparent," he says. Alas, perhaps some questions are better left to logicians.

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Further Reading

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Milestones

CS Awards

NEVANLINNA PRIZE

Daniel Spielman, a professor of computer science and applied mathematics at Yale University, won the Rolf Nevanlinna Prize, one of the highest honors in the field of mathematics, from the International Mathematical Union. The Nevanlinna Prize recognizes researchers under the age of 40 for "outstanding contributions in mathematical aspects of information science." Spielman's research has included smoothed analysis of linear programming, algorithms for graph-based codes, and applications of graph theory to numerical computing.

"The same way that physicists grow up dreaming about winning the Nobel Prize, I've dreamed of winning the Nevanlinna Prize ever since I was a graduate student," Spielman said in a statement. "I was in shock when László Lovász, the president of the International Mathematical Union, called me up to tell me that I had won. I had to hear him say it a few times before I believed him. It is an incredible honor. Many of my heroes have won this prize."

MICROSOFT AWARD

Cheryl Arnett from Sunset Elementary School in Craig, CO, and Rawya Shatila from Maskassed Khalil Shehab School in Beirut, Lebanon, won first place in the 2010 U.S. Innovative Education Forum, a Microsoft-sponsored competition for teachers who use technology in their curriculum to improve student learning. Arnett and Shatila's joint project, called "Digital Stories: A Celebration of Learning and Culture," connected Arnett's class of first- and second-graders in Craig, CO, to Shatila's second-graders in Beirut. The two teachers, who had never met prior to their collaboration, used wikis, blogs, and online mapping tools to share stories and activities to help students increase their global awareness of the similarities and differences between children from different nations. Arnett and Shatila will represent the United States at the Worldwide Innovative Education Forum in South Africa this fall.

—Jack Rosenberger