

ADAM KOHLHAAS

Multimodal Large Language Modeling

As impressive as chatbots like OpenAl's ChatGPT and Google's Bard are, one feature they lack is multimodal integration of text and images for both input and output. Researchers in Carnegie Mellon University's Machine Learning Department (MLD) and Language Technologies Institute (LTI) have developed a multimodal large language model (LLM) named Generating Images with Large Language Models (GILL). GILL is one of the first models that can process and produce layered images and text, where images and text can be provided as the inputs and the outputs.

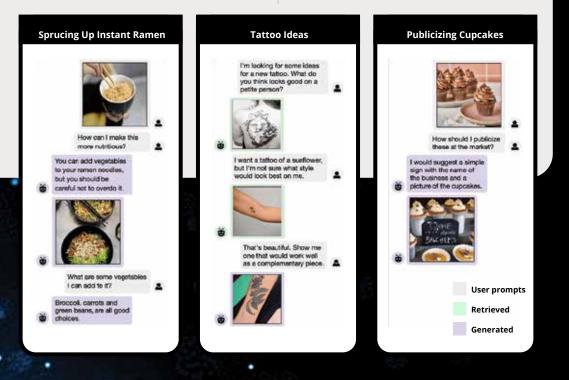
GILL accepts both images and text as input and determines the best modality in which to respond. Along with plain text responses, it can generate images when a more creative answer is needed or an existing image is not available. It can also pull images from an archive in situations requiring a factual response. This flexibility allows the model to seamlessly generate relevant images and layer them with text outputs, producing image and text responses that may be more illustrative than text-only outputs.

"I'm excited about GILL because it is one of the first models that can process image-text inputs to generate text interleaved with retrieved and generated images," said **Jing Yu Koh**, an MLD Ph.D. student and one of GILL's co-authors. "It is more general than previous multimodal language models and has the potential for a wide set of applications."

To achieve this unique combination of abilities, CMU researchers proposed an efficient mapping network to ground the output space of a frozen text-only LLM to the input space of a frozen text-to-image generation model. This action allows the LLM to be efficiently trained to produce vector embeddings compatible with those of the generation model. GILL exhibits a wider range of capabilities compared to prior multimodal language models (such as the ability to generate novel images) and outperforms non-LLM-based generation models across several text-to-image tasks that measure context dependence.

The CMU members involved in this research include Koh; **Daniel Fried**, an assistant professor in the LTI; and **Ruslan Salakhutdinov**, a professor in MLD. They're excited about the potential that their method has in future applications.

"GILL is modular, and our approach is model agnostic, meaning that it will likely benefit from applying stronger LLMs and visual models released in the future," Koh said.





Computer Science at CMU underpins divergent fields and endeavors in today's world, all of which LINK SCS to profound advances in art, culture, nature, the sciences and beyond.

theLINK

Fall 2023 | Issue 17.2 The Link is the magazine of Carnegie Mellon University's School of Computer Science, published for alumni, students, faculty, staff and friends. Copyright 2023 Carnegie Mellon University. All rights reserved.

Publisher Martial He<u>bert</u>

Editor Kevin O'Connell

Contributing Writers

Aaron Aupperlee, Susie Cribbs (DC 2000, 2006), Stacey Federoff, Niki Kapsambelis, Adam Kohlhaas, Haley R. Moore, Kevin O'Connell, Chris Quirk, Byron Spice, Matt Wein

Design Susie Hernishin

Photography Kevin Lorenzi, Provenza et al, Nature Medicine, 202, Nate Smallwood

Illustration Susie Hernishin

Office of the Dean Gates Center for Computer Science Carnegie Mellon University 4902 Forbes Avenue Pittsburgh, PA 15213 cs.cmu.edu

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Obtain general information about Carnegie Mellon University by calling 412-268-2000.

magazine@cs.cmu.edu

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Layers of Foundation

hope you were able to peruse the last issue, a special edition of The LINK magazine which provided an overview of our work in space exploration. Dedicating an entire issue to a single topic not only revealed the complexity of the topic, but allowed us a look at the depth and breadth of our work in the field.

As scientists and researchers, our work inherently builds on the foundations of those who have researched before us. In turn, the contributions we put forth become the foundation upon which future research and scientific development will rest. We understand this as a matter of course, part of the stock-in-trade of our work.

Historians, journalists and academic societies like to take the more cursory view and often try to point attention toward certain achievements as having more gravitas than others. While this has some merit, we in the scientific community always do well to respect those who have come before us, collaborated and competed with us, in an unending quest to understand. Yes, all ships rise together.

In the foundation and building of our school, the specific contributions of each person has been instrumental to our success and put SCS at the forefront of research and teaching. As with many of our efforts, it is a fool's errand to try to single out "the most" foundational, instrumental or important. All influences can be felt in the ground on which we stand. You may agree that individual perspective on the matter becomes paramount. When I first arrived at CMU, I found myself in awe of giants in the field to whom I had access. Herb Simon, Allen Newell, Red Whittaker, Mary Shaw, Raj Reddy and so many others. Their influence on my work and life cannot be overstated. In SCS, we have strived to continue to bring the best minds to campus to build each new foundational layer upon the last, in order to continue to offer world-class experiences for those in our community, for the betterment of all.

And so, you will find in this issue a handful of the stories centered on the idea of foundational work in SCS. Going forward we will continue telling the stories of our foundation $-\log g$ standing and more recent - not only because they are important, but because they reveal the design of our mission to make the world a better place.

Martial Hebert Dean, School of Computer Science



COMPUTERS THAT THINK

A t a commencement ceremony for doctoral candidates in the 1990s, **Manuela Veloso** remembers vividly the keynote speaker: Herbert Simon, Nobel laureate, Turing Award winner, artificial intelligence pioneer and one of her most influential mentors at Carnegie Mellon University.

She recalls how Simon, a giant in the field, exhorted the new Ph.D.s: "Do not live your life as a zero-sum game."

Researchers, he explained, do not need to win at someone else's expense. In other words, "Everybody has some value," Veloso paraphrased.

> At the time, she was a young faculty member; today, she is head of AI research for J.P. Morgan Chase and Herbert A. Simon University Professor Emerita. And she credits the

influence of Simon and his frequent collaborator, Allen Newell, with shaping her approach to problem solving.

Veloso is not alone, but quite possibly, many Al students and researchers who carry the torch

BOTH OF THEM HAD ONE FOOT IN COGNITIVE SCIENCE AND THE OTHER FOOT IN AI.

Manuela Veloso, Herbert A. Simon

Professor Emerita

- RAJ REDDY, MOZA BINT UNIVERSITY PROFESSOR lit by Simon and Newell are not fully aware of the breadth of their influence. At the northwest corner of the Carnegie Mellon University campus stands a buff brick building, Newell Simon Hall, that is the physical embodiment of their legacy; the work undertaken within its walls, and by the people who have passed through its doors, stands on the foundation of ideas that Simon and Newell championed.

Yet **Raj Reddy** hypothesizes that

nypotnesizes that most of the people who now work in that building, which greets visitors with a robotic receptionist, have only a vague idea about who either man



truly was. Reddy, the Moza Bint Nasser University Professor, counts himself among those who not only worked with Simon and Newell, but was directly impacted as they built their legacy.

"Basically, both of them had one foot in cognitive science and the other foot in AI," Reddy said. "They were trying to build models that would explain how a human being thinks and acts."

Reddy arrived at Carnegie Mellon 54 years ago, long before there was a buff brick building, or a robot receptionist or a Robotics Institute (of which he would become the founding director). There was no School of Computer Science, for which Reddy later would become dean; there was just a small computer science department with a handful of professors and a few more associates.

Within the span of a decade, all of that would change dramatically, and Allen Newell and Herb Simon were the catalysts. Exuberant in their collaboration, excited about ideas, curious not only about their own research but also about the world, they would together help create an entirely new discipline that would touch every corner of our culture — while also asking the critical question of how it would impact human lives.

NIKI KAPSAMBELIS

Trailblazers: EXPLORING THE LEGACY OF ALLEN **NEWELL** AND HERBERT **SIMON**



THE **THINKING** MACHINE

Newell met Simon, a political scientist 11 years his senior, at the RAND Corporation, a nonprofit think tank dedicated to research and global policy. At the time, they were focused on air defense systems. And in the early 1950s, many considered computers to be glorified calculators, meant to crunch numbers and little else.

Their epiphany happened when they realized that computers could represent and manipulate symbols and weren't just limited to numbers. In fact, computers could interpret patterns based on prior experience, which humans also do. From there, Newell and Simon hypothesized that computers could simulate decision-making.

ONE OF THE FIRST RULES OF SCIENCE IS IF SOMEBODY DELIVERS A SECRET WEAPON TO YOU, YOU BETTER USE IT.

— HERBERT SIMON, PITTSBURGH POST-GAZETTE, 2000

"That seemed, to me, a tremendous breakthrough," Simon told the Pittsburgh Post-Gazette in 2000. "And one of the first rules of science is if somebody delivers a secret weapon to you, you better use it."

Through the fall of 1955, they created a program that would allow a computer to "discover" the proofs of geometry theorems; by the end of December, they got it to work, prompting Simon to tell his students in January 1956: "Over Christmas, Allen Newell and I invented a thinking machine."

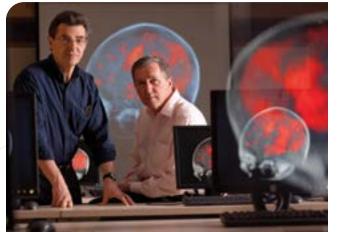
In the years that followed, their collaboration would generate a field that expanded well beyond the world of geometry problems, bringing to bear concepts that were the stuff of science fiction when they started; but always, in the DNA of each new initiative of artificial intelligence, lies a germ of the seed they planted. Nearly a half-century and a Nobel Prize later, Simon would continue to frame their AI work, characteristically, through the lens of what it meant for people; he still didn't want research to be a zero-sum game. He wanted to give people the tools to harness the broader world of knowledge that surrounds them: "Human knowledge has been changing from the word go," he told the Post-Gazette. "One of my big interests has been to see how we can give computers those capabilities. Because I don't care how big and fast computers are, they're not as big and fast as the world."

AN ENDURING

For **Tom Mitchell**, Founders University Professor, the application of human cognition to machine learning has long been a hallmark of Carnegie Mellon — one that still influences his own work. For example, one line of his research compares brain scans of people looking at sentences that also have been shown to an artificial intelligence program, similar to an early version of ChatGPT. The computer was able to predict the brain activity of the person reading the sentence.

He recalls a course that he team-taught with Newell and former SCS professor **Geoffrey Hinton** (who would later win the 2018 Turing Award) that focused on architectures for intelligence. The concept was to build integrated AI systems that incorporated things that humans do: seeing, hearing, planning and playing games, all while improving automatically over time from experience.

Tom Mitchell (right) pictured with Marcel Just, D.O. Hebb Professor of Psychology, University Professor of Psychology.



ROBOTICS ENDS UP BEING A GREAT DRIVER FOR LOOKING AT HOW TO PULL TOGETHER ALL THESE DIFFERENT ASPECTS OF INTELLIGENCE.

--- TOM MITCHELL, FOUNDERS UNIVERSITY PROFESSOR

"It was one of the most fun things I had done, academically, to that point," Mitchell said, adding that it was one reason why he decided to stay at Carnegie Mellon after first arriving as a visiting professor.

And today, that same work is reflected in the Robotics Institute, he noted. "Robotics ends up being a great driver for looking at how to pull together all these different aspects of intelligence," said Mitchell.

Newell and Simon's work in vision and perception provided the foundation for Martial Hebert's research in object recognition, scene understanding and perception for autonomous systems, enabling robots to perceive and interpret their environment. Takeo Kanade's development of algorithms that assist in object recognition, image understanding and autonomous navigation align with Simon and Newell's emphasis on creating perception and cognition in machines.

Their legacy touches virtually every corner of the School of Computer Science: that robot who greets visitors at the entrance? It uses research drawing from their emphasis on understanding human behavior. **Chris Atkeson**, professor in the RI and HCII, focuses on human-robot interaction, building on the principles of cognitive architectures and human behavior that Simon and Newell emphasized. Decision-making and bounded rationality, two other hallmarks of Atkeson's research, inform assistant teaching professor **Stephanie Rosenthal's** development of algorithms that allow for planning and scheduling in changing environments.

MARY SHAW **AI INNOVATOR**

Mary Shaw, the A.J. Perlis Professor of Computer Science, has spent her career pioneering the fields of software engineering, formal methods and computer science education. With a distinguished career spanning decades, Shaw has been an innovator in the field through her research, teaching and leadership.

Born in 1943, Shaw earned a bachelor's degree in mathematics in 1965, followed by a master's degree in computer science in 1968.

Mary Shaw was a driving force in the development of formal methods, which involve mathematical techniques to ensure the correctness of software systems. Her work improved software reliability and quality through rigorous analysis



and verification methods. She played a crucial role in the development of the Software Engineering Institute (SEI) at Carnegie Mellon University, where she led the effort to create the Capability Maturity Model (CMM). This model became an industry standard for evaluating and improving software development processes, promoting best practices and organizational maturity.

Beyond her research, Shaw has been deeply involved in reshaping computer science education. She has advocated for a holistic approach that combines theory and practice, emphasizing the importance of both technical skills and problemsolving abilities. Her educational initiatives have influenced curricula worldwide, ensuring that future generations of computer scientists are well-prepared to tackle real-world challenges. Her emphasis on rigorous methodologies and formal analysis has had implications for AI systems' design, verification and safety. As AI technologies continue to advance, Shaw's work remains relevant in ensuring the reliability of AI applications.

Shaw was named an IEEE Fellow in 2010 and is an ACM Fellow. She received the 2011 ACM SIGSOFT Distinguished Service Award for her outstanding leadership in software engineering. Shaw was awarded the National Medal of Technology and Innovation in 2014, the highest honor for technical progress in the U.S.

WHAT IS **RESEARCH**?

Veloso remembers distinctly a lecture Newell gave in December 1991 called "Desires and Diversions," given seven months before his death, when he talked about his life in research: how he was driven by the overarching goal of understanding the human mind, but a handful of diversions from that goal produced major scientific achievements on their own.

"My research was a product of that lecture," Veloso recalled. "I never read science fiction; I never cared about robots."

But the idea of exploring and integrating different functions intrigued her, and she was off on a career of her own, developing intelligent robots capable of learning and interacting with humans and their environment.

She credits Simon with helping her frame problems. From her arrival at Carnegie Mellon in 1986 until Simon's death in 2000, Veloso estimates she sat in 14 of his lectures that asked the question: What is research?

COMPUTERS THINKING DON'T MAKE YOU EXPENDABLE.

- HERBERT SIMON

"He was very consistent in saying that basically the research needs to be something that was novel, in the sense that other people had not done this. People had to care about it. And you had to publish. You had to let other people know what you were doing." — MANUELA VELOSO

Veloso still applies these principles to her work at JP Morgan Chase, and she believes that Simon, who died 18 years before she took her position there, would have been proud of her. She would have loved to discuss the role of AI in organizations with him.

She met with Simon often as a young faculty member. She remembered an occasion when she was upset — a paper was rejected, or some other aspect of her career had not gone as she'd hoped. Simon asked her what was wrong.

"Herb, you have a Nobel Prize. You won't understand," she said.

But Simon did understand. He told her she was mistaken to assess the worth of her work based on outside opinion; instead, she should know herself if her work was good, independent of whether it was accepted or rejected somewhere.

Years later, not long before he died, Simon was asked whether people would become expendable if computers could think for themselves. His answer hewed closely to what he told Veloso about knowing her own worth.

"Computers thinking don't make you expendable," he told the Post-Gazette. "Maybe we ought to think of worth in terms of our ability to get along as a part of nature, rather than being the lords over nature."

Furthermore, he added: "Technology may create a condition, but the questions are, what do we do about ourselves? We better understand ourselves pretty clearly, and we better find ways to like ourselves." A THOUSAND FLOWERS

Both Simon and Newell embraced an openmindedness that continues today, according to Raj Reddy: "It is the culture of the whole school; how we act, and behave, and think and empower people."

Newell got up early every morning, working at home before coming to the office at lunchtime. For the rest of the day, all he did was meet with people and give them advice: "It didn't have to be AI. It could be anything," Reddy said. "That made a major difference to all the younger faculty members in the department, me especially."



Mitchell recalls how Newell and his wife bought him housewarming gifts when he moved to Pittsburgh and made sure he felt comfortable. A tall man with an engaging smile, Newell was always happy to see people, always asking what they were interested in or working on. BOTH SIMON AND NEWELL EMBRACED AN OPEN-MINDEDNESS THAT CONTINUES TODAY.

"He cared what was going on in your life, and he wanted all that to be good," Mitchell said. "He wanted to find places where you and he didn't think the same thing. He was always searching for where you didn't agree with him. And he'd say, 'Well, that's interesting. Let's dig into that.""

In "Desires and Diversions," Newell gave his audience several maxims that he lived by. One of them still resonates today, made even more poignant by the fact that he died a few months later: "Choose a final project that will outlast you," though he tempered it with another maxim: "Everything must wait until its time."

For Newell, science was the art of the possible, and the role of the scientist was to pass the torch so the idea could expand to its next incarnation, when the time was right.

"They were eclectic. They were broad enough in their thinking," Reddy said. "They were saying: 'Let's spread our wings and let a thousand flowers bloom.""

To this day, the multidisciplinary approach might be the most enduring legacy of Simon and Newell, because it extends across Carnegie Mellon's campus, not just in the halls of the building that bears their name. And the principles that guided their early "thinking machine" are infused in every corner of society around the globe.

It is, for both men, the project that outlived them.

• WE OUGHT TO THINK OF WORTH IN TERMS OF OUR ABILITY TO GET ALONG AS A PART OF NATURE, RATHER THAN BEING THE LORDS OVER NATURE.

— HERBERT SIMON



BUILDING BLOCKS TO COMMUNICATE

PRINCIPLES Bob Harper, Professor of Computer Science **OF PROGRAMMING**

The Theory Underlying Computing Languages

BYRON SPICE AND KEVIN O'CONNELL

If you ask Computer Science Professor Bob Harper, he'll tell you that "Mommy, go'ed to the store" is more than a statement a small child might make. Though grammatically incorrect, the statement demonstrates that the child understands that adding "ed" to the end of a verb will make it past tense. By using this simple algorithm - defined as a series of sequential steps involved in any process - the child generates a sentence they have never heard anyone speak, and has learned without being taught how to use a variable as a part of the language acquisition process.

Harper is a member of the School of Computer Science's Principles of Programming group (PoP), which focuses more on the philosophy behind how humans communicate with machines and each other and less on the subtleties of syntax in programming code. "Whatever a program is, it's a way of expressing ideas," said Harper. "Fundamentally, what we're doing is talking to each other."

Even though we generally think of algorithms strictly in terms of computing, that concept may be limiting, and human cognition shouldn't be overlooked. The late Dutch mathematician and philosopher L.E.J. Brouwer promoted the idea that math is a linguistic activity and that, as with the child who can fashion a primitive sentence, humans are born with an instinctive understanding of the concept of an algorithm – distinguishing them from other animals.

This concept, known as "intuitionism," flew in the face of conventional wisdom at the time. But it makes sense to Harper. "It's a very down-to-earth conception, which I like," he said.

Theory A and Theory B

The theory of computation developed in the mid-20th century has two major schools of thought. The first, led by British mathematician Alan Turing, conceived of programs as read and write functions that acted on computer memory. Commonly known as Theory A, Turing's theory is based on abstract mathematical models of computation, or Turing machines, and defines computability in terms of what a Turing machine can compute in step-by-step execution of algorithms.

The second theory, Theory B, originated with American mathematician and computer scientist Alonzo Church, who defined computability in terms of functions that can be computed using a formal system for expressing computation, known as lambda calculus (λ -calculus).

Church's idea enabled fully expressive languages that didn't rely on numbers, but on deductive reasoning. He proposed that any effectively calculable function can be expressed in lambda calculus. With lambda calculus and its use of variables at its core, Theory B profoundly influenced the development of programming languages, especially functional programming languages such as Lisp and Haskell. It also played a role in the theory of programming semantics.

Turing's theory has been embraced by most American computer science departments, while Church's theory enjoys more popularity in Europe, Harper said. And while both theories have been proven to be equally computable, Harper and his PoP colleagues feel the approach of the latter lends itself to a more complete and therefore more productive understanding of programming.

"It's called Church's thesis, but it should be called Church's law," Harper said. "As far as I'm aware, it's the only scientific law in computer science." There's nothing directly analogous to it in a Turing machine, he added.

Though he's not part of PoP, but rather "more of an algorithms guy," Daniel Sleator, a professor in the Computer Science Department, tends to agree with Harper — at least in theory — about the usefulness of programming based on Church's approach.

"In a language like Java or C++, you have to festoon your program with all the types of all the objects in the program," Sleator said. "You have to write them all out. Whereas functional languages can derive the type based on the way you're using these variables." Sleator also noted that his programs almost always work – and work the first time – when programming in OCaml rather than when writing in Java or C++, which often need debugging.

The PoP Group

CMU has been the leading American outpost for Theory B since Dana Scott, Church's former student and a Turing Award winner, joined the Computer Science Department in 1982. Scott recruited such stalwarts to the department as John Reynolds, Stephen Brookes, Frank Pfenning and Peter Lee, "making CMU one of the premier places in the world for PoP," Harper added.

Church's use of variables demands that programmers pay attention to how they compose their programs. PoP places a strong emphasis on formal methods, a branch of computer

science that uses mathematical techniques to specify and verify software systems. These methods also delve into formal verification, which involves mathematically proving the correctness of software and ensuring it behaves as intended. This focus on formality is more rigorous and theoretical compared to standard programming practices that often rely on testing and debugging.



FALL 2023



Dana Scott, Hillman University Professor of Computer Science, Philosophy and Mathematical Logic (Emeritus)

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Harper worries that most computer scientists think they know about programming languages but fail to truly understand the philosophical underpinnings of languages and the computation involved in them.



Daniel Sleator, Professor in CSD

Sleator understands Harper's concerns. Through his years of teaching programming, Sleator has learned to value languages based on both theories, and also respects the practical idea of using different languages for different purposes — and thinking about a problem creatively enough to know when to employ a certain language to accomplish a particular task. The danger comes in over relying on languages students learn early in their education, which can lead to inefficient programs.

"The kids love to use Python, but it's not a great language for algorithmic programming. It's slow," Sleator said. "The point of algorithms is you'll want your code to run fast. That's the whole point of the field – we figure out how to speed up algorithms."



Developments in Type Theory

Under Harper's guidance, one area of emphasis in PoP's work has been type theory - a foundational concept that deals with classifying data based on its category or type. Type theory provides a formal framework for specifying and verifying the behavior of programs, ensuring they operate correctly and safely.

Harper's work specifically has hugely influenced type theory, garnering him the 2021 ACM SIGPLAN Programming Languages Achievement Award for his impact on the foundation and design of programming languages, type systems and formal methods.

His work on type systems for programming languages also helped create languages that are both expressive and safe, striking a balance between flexibility and correctness. One obvious example is Standard ML (sML), a statically typed functional programming language known for its powerful type system that has influenced the development of subsequent programming languages like OCaml, Haskell and others.

In addition, Harper is known for his work with type systems for program modules, which are separable components that are needed to manage the sheer complexity of programs and to help share code across implementations.

A sophisticated form of type theory known as dependent types, where types can depend on values, has been another area of focus for Harper. Dependent types prove extremely valuable in ensuring program correctness and have applications in areas like formal verification.

For a deeper dive into Harper's work, including his work on dependent types, check out the book, "Practical Foundations for Programming Languages," which explores the theory and practical aspects of dependent types and is the text he uses for the undergraduate course he teaches on Foundations of Programming Languages.

Toward the Future

Since its founding, the PoP group has clearly made important contributions and exerted a large influence on the programming languages field. Current members and alumni have applied PoP ideas to fields beyond type theory and formal verification. Technologies from block chain to quantum computing have benefited from programming languages rooted in lambda calculus because of their elegance, simplicity and efficiency. And there are many examples close to home in SCS, even if we

begin talking about blending the ideas within Theories A and B.

A few examples: Guy Blelloch, a professor in CSD, studies parallelism - particularly efficient parallel algorithms and data structures – and his work holds wide-ranging implications for concurrent computing systems.

Harper's work in graduate school in the later 1980s at the University of Edinburgh led to development of the Logical Framework (LF), also known as the Edinburgh Logical Framework (ELF). LF, co-authored by Furio Honsell and Gordon Plotkin, which provides a means to define (or present) logics and is based on a general treatment of syntax, rules and proofs by means of a typed λ -calculus with dependent types.

> Guy Blelloch, Professor and Associate Dean for Undergraduate Programs in CSD



Computer Language Archetype



Laying the foundation for the Principles of Programming group at CMU, as well as for nearly all programming languages since, Alan Jay Perlis (April 1, 1922 - February 7, 1990) was a visionary computer scientist who reshaped the landscape of programming languages, software engineering and computer science education. Born in Pittsburgh, Perlis made many seminal contributions while a professor at CMU.

Perlis co-developed Fortran, the first programming language specifically designed for symbolic mathematical computations, which significantly influenced the development of subsequent programming languages. He also played a crucial role in the early development of Lisp, one of the oldest high-level programming languages. Lisp introduced the concept of symbolic processing and recursion.

Perlis was an early pioneer in the development of time-sharing systems, which allow multiple users to interact with a computer simultaneously, laving the foundation for concurrent computing systems. Additionally, he advocated for structured programming and software engineering principles, emphasizing the importance of clear and modular code design to improve program reliability and maintainability.

Perlis's oft quoted book "Epigrams in Programming" is a witty collection of thought-provoking statements about programming and computer science which continue to provide insights and guidance for programmers today. His emphasis on the importance of teaching programming as a problem-solving skill continues to impact curriculum development at CMU and the field of computer science pedagogy more broadly.

Alan Perlis was the first recipient of the ACM Turing Award in 1966 for his contributions to computer programming languages, and his work, ideas and accomplishments continue to influence how we design, write, and teach software today.

After Harper came to CMU, he collaborated with Frank Pfenning and Karl Crary, both professors of computer science and PoP members, on work with LF, resulting in a powerful tool for precisely and formally specifying the syntax and semantics of programming languages. Harper worked closely with Crary on the verification of an

and logics.

important property of a language called type

safety, which has mechanized the proof of safety of

the entire Standard ML language using the Twelf

implementation of LF developed by Pfenning and

his students. Twelf, a research project funded by the

National Science Foundation, provides a uniform

and proving properties of programming languages

In addition to these works and the many others

some languages rooted in Turing machine-style

traditionally thought to be within the domain of

Theory B and λ -calculus. Popular languages like

C++ are adopting concepts rooted in Church's

"In C++ there's a type called 'Auto,' which

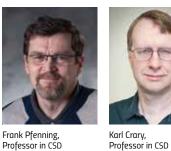
says, 'The programmer can write 'Auto' in front

theory that PoP championed decades ago.

computation are beginning to take on aspects

meta-language for specifying, implementing

happening within CMU, Sleator noted that



Professor in CSD

of the variable instead of saying 'Integer Float,' or whatever it is, and simply say 'Auto,' and then the language can decide what type it is," Sleator said. "They were doing that 30 years ago in these sML-type languages."

The recent inclusion of these lambda expressions

in languages like C++, demonstrates that programmers value such functions and want them in the languages they use. Sleator said.

And while the group has had — and will continue to have – an incredible, practical impact on programming languages, Harper takes a more philosophical approach.

He sees, at its core, something much deeper in their work.

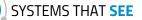
"Computation is fundamental to who we are as a species," Harper said. "Computing, so conceived, is more fundamental than math."

As the gap between the two theories draws closer, in some circles, those working closely in the theory of programming languages are finding value beyond the traditional approaches to programming a computer or writing a code. We are learning far more about ourselves.

"God is trying to tell us something," said Harper.

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CHRIS QUIRK

DELCO

COMPUTER VISION: Eyes for the Future of Al

Aside from the corporate decals plastered on the sides, the unassuming 1990 Pontiac Trans Sport — alias NavLab 5 could just as easily be filled with kids on their way to soccer practice. But inside, along with a jumble of cables and an open laptop beside the driver's seat, a front-facing camera lodged on the rearview mirror shuttles images of the road ahead to as much computer as the 9-volt cigarette lighter can power.

CMU research scientist Dean Pomerleau (right) and (then)

graduate student Todd Jochem appear in front of NavLab5.

I TOLD MY STUDENTS, YOU WILL SHARE YOUR FATE WITH THE SOFTWARE, SO YOU'D BETTER MAKE IT GOOD!'

Takeo Kanade, Founders University Professor

The year was 1995, and the mission, No Hands Across America, a long-distance autonomous driving test in which NavLab 5 would transport CMU research scientist Dean Pomerleau and graduate student Todd Jochem the 3,000 miles from Pittsburgh to San Diego, without a human being so much as touching the steering wheel. At least they hoped. "I told my students, 'You will share your fate with the software, so you'd better make it good!'" said Takeo Kanade, the Founders University Professor of Computer Science, who was the faculty lead on the project.

The term computer vision covers everything from image classification to facial identification to medical imaging to self-driving vehicles. Martial Hebert, dean of the School of Computer Science and a computer vision pioneer who developed the range sensor for NavLab, defines the diverse range of applications with elegant simplicity. "Computer vision is fundamentally the idea of extracting higher level information from visual data."



Noted car guy and former late night TV talk show host Jay Leno (left) receives a tour of NavLab 5 outside the Tonight Show studios.

As it turned out, during the No Hands Across America drive, NavLab 5 achieved a 98.2% autonomous driving rate. The trek made national news, and even caught the eye of car enthusiast Jay Leno, who invited Pomerleau and Jochem to stop by the Tonight Show studio lot for a visit. Kanade, surmised at the time that full autonomous driving would take three years. "It took 30," he said. "I was only off by an order of magnitude."

Despite hopeful beginnings followed by — at times — glacial progress, researchers in computer vision are now probing superhuman possibilities that are expanding the fields of transportation, health,

security and more. "We



of the Robotics Institute.

want to change the definition of what a camera is," said Srinivasa Narasimhan, professor of the Robotics Institute.

Today, as driverless vehicles free of steering wheels or other manual controls are about to hit the streets, the early days of computer vision seem as distant as dial-up internet. But it bears remembering the herculean labor that was required to achieve even the most elementary tasks of computer vision, and how tomorrow's possibilities rely on the foundational work of Hebert, Kanade and others.

Srinivasa Narasimhan, Professor

Dean of SCS

Martial Hebert,



Among the many awards and honors he's received over his career, Takeo Kanade is shown here in Japan receiving the 2016 Kyoto Prize for Advanced Technology. The international award is presented by the Inamori Foundation to individuals for significant contributions to the scientific, cultural and spiritual betterment of humankind.

Kanade and his colleagues began NavLab in true garage-project style — they attached a camera and some hardware to a cart. "There wasn't even a laptop on board, so the robot cart couldn't operate on its own. Can you imagine?" Kanade said. A nearby computer sent maneuvering information to the cart using a radio signal, for which the NavLab team had to acquire a broadcast license. "It was tedious," Kanade recalled. "Initially, we moved the cart one centimeter per second. You could barely tell it was moving."

By any measure Kanade ranks as one of the groundbreaking figures in computer vision. He built his first major invention, a facial recognition tool, in 1970. To train the system, he took his camera and image digitization system that he had built to the Japan World Exposition in Osaka, where visitors would sit for the 10 seconds it took to digitize their facial image in exchange for a small prize. "We gathered a thousand images," Kanade said. "At the time, it was probably the world's biggest image database."

THE LINK



A line of cameras provides Super Bowl XXXV production crews 360-degree replays of the on-field action similar to special effects used in the film "The Matrix."

EyeVision in Super Bowl XXXV

In 2001, CBS Sports brought Kanade and his team at Carnegie Mellon to Super Bowl XXXV, to create a new video replay system. Kanade created EyeVision, which showed viewers action on the field from virtually any angle, rotating around a play to reveal details that single point-of-view cameras could not capture. "There was no real secret to it," said Kanade. "We had seen that effect in the movie, 'The Matrix', and CBS came to me and asked if I could do something similar. The big difference from the movie was that instead of a single position where an actor would stand, we had to cover the whole football field."

Kanade first set 33 cameras around the stadium, spanning 270 degrees of view. While the principle of the system seemed self-evident to Kanade, the execution was another story. Kanade built a massive computer processing apparatus that swallowed all input from all the cameras — including information on zoom length, angle and image content — and synthesized it into a single, seamless, rotating image for viewers. A camera operator seated at a custom-built fake camera carriage, and watching the game on a video monitor, controlled all the EyeVision cameras in tandem by following the action on screen. On game day, it didn't take long before the head producer repeatedly went to EyeVision replays. Nearly 85 million viewers watched the game nationwide, and today almost all major sports use replay systems emulating EyeVision's innovation for broadcast or replay reviews.





A lack of computational power limited computer vision research early on. But now, more powerful computer vision systems draw power from more powerful computational systems. "We've seen an exponential rate of advances," said Hebert. "Another development is that over time, researchers have created a set of tools and building blocks for the creation of more complex functionality. You don't have to reinvent the wheel every time." Much of Hebert's early research centered on finding ways to economize information and processing systems so the precious computational capacities of early computer vision systems could be used in full. "Techniques today are very different," said Hebert. "But the early research helped identify key challenges of computer vision."



These advances now empower researchers to find new ways to explore the visual world. **László Jeni**, assistant research professor in the Robotics Institute,

has created a face interpretation tool to help people with vision impairment recognize those around them and to be able to interact with them more easily. The tool consists of a small, head-mounted camera and earpiece that the user wears, along with a processing unit on the arm. As someone approaches, the tool scans the person's face and analyzes their expression, for a smile or consternation. It then gives a simple audio cue as to the emotional state of a person, such as, "Nick is approaching, and looks very happy," so the wearer can greet and start a conversation with Nick. "It recognizes what we call facial action units. These are elementary facial characteristics, like raising your eyebrows, a smile or a smirk, and each has a separate code," Jeni explained. "Humans use a lot of different communication channels, and verbal is just one of them."

Top: A vision-impaired user wearing a head-mounted camera and a processing unit attached to her arm interacts with another person. Bottom: A frame from the corresponding processed video stream, featuring 3D face tracking, face recognition, and automated facial affect recognition of the interacting individual.

⁶⁶ HUMANS USE A LOT OF DIFFERENT COMMUNICATION CHANNELS, AND VERBAL IS JUST ONE OF THEM.

László Jeni, Assistant Research Professor in RI

In addition, Jeni uses computer vision face mapping analysis as part of a treatment for obsessivecompulsive disorder in patients who have not responded to medication or cognitive behavioral therapy. The therapeutic device employs deep brain stimulation via an electrode embedded in the subcortical area of the brain. The stimulation can help reduce anxiety and distress associated with OCD. The electrode stimulates the targeted brain region while a computerized face mapping tool looks at the expression of the patient and analyzes the emotional response. "The face and body responses are the motor outputs of the brain region you are stimulating," said Jeni. "You can get a semantic meaning from that and tell whether the treatment is working. It's very important to objectively measure behavior in order to improve outcomes. The face mapping analysis provides an interpretation of what is happening inside the patient that I can use to evaluate the deep brain stimulation."



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Tartan Racing Wins DARPA Challenge, Establishes Autonomous Legacy



CMU's Tartan Racing team victory in the 2007 Defense Advanced Research Projects Agency's (DARPA) Grand Challenge was a pivotal event in the development of autonomous vehicles, the repercussions of which we all feel to this day. And CMU's advanced

use of computer vision helped Tartan Racing, led by William "Red" Whittaker, Faculty Emeritus, to victory and showcased the capabilities of autonomous vehicles in complex, real-world scenarios.

DARPA, organized the competition to encourage the development of autonomous vehicles capable of navigating a complex desert course. The goal was to advance the state of the art in autonomous robotics and promote technologies with potential military applications.

Whittaker's leadership and CMU's innovative use of computer vision technologies were instrumental in the victory. Being equipped with an advanced array of sensors, which included cameras, lidar and radar, the autonomous vehicle "Boss" held a comprehensive view of its environment — a significant advantage over the competition. Tartan Racing's computer vision algorithms processed the data from these sensors, allowing Boss to recognize obstacles, navigate the course and make real-time decisions to avoid collisions.

The success of the DARPA Grand Challenge has had a lasting impact on the field of robotics and autonomous systems, and establishing Pittsburgh as a hub for further research and development.



Seeing Around and Through

Computer vision researchers now work to see the unseeable — seeing around corners, clarifying images taken amidst impenetrable murk, and using visual information to record sound. Some of these innovations call to mind science fiction.



loannis Gkioulekas (pictured) and Srinivasa Narasimhan are creating a photon selection device to essentially see through objects.

Narasimhan and loannis Gkioulekas, assistant professor of computer science, are creating a photon selection device to register images in foggy or near opaque conditions. "My lab is about seeing through things," said Narasimhan. In an early project, Narasimhan built a smart headlight that helps drivers navigate rain and snowstorms by detecting the motion of drops or snowflakes, and reducing headlight illumination selectively to decrease glare. More recently, to capture images in murky underwater environments, the duo grabs the photons best suited to create a picture of the target object. "In muddy water, for example, 99.9% of the photons are just scattered," Narasimhan said. "To get the right photons, we select particular photons that are specularly reflected, according to Fermat's principle. You look at where the photon is coming from, the time of flight, time of arrival, even thermal information. We are very much interested in using light, sound and heat together."

What we are about now is creating the cameras of the future.

Ioannis Gkioulekas, Assistant Professor of Computer Science

Walls are no obstacle for Gkioulekas and company. Expanding on research begun at the Massachusetts Institute of Technology, Gkioulekas developed a camera that reconstructs the picture of a subject behind a separating barrier, using light bounced off an adjacent wall. Using a technique similar to lidar, the camera fires a beam of light off the wall, which then bounces off an object behind the barrier and returns. The camera measures the time it takes for the light beams to get back to the camera and records a timestamp. These intervals are measured in picoseconds, or trillionths of a second. "You shoot maybe a thousand pulses at a time, and go point-by-point to capture depth," said Gkioulekas. "When you process that you get a very detailed, 3D reconstruction. We're still working on this, but we've done imaging where you can read the word 'Liberty' on a quarter from around a corner."

For an example of sound and vision working together in computer vision, Narasimhan and his colleagues are developing a camera using dual-shutter vibration. This camera picks up the imperceptible effect of sound vibrations on surfaces and separates them. "A microphone will capture all the sound that reaches it. If there are two people talking, or people playing drums or musical instruments, you get the sum of their sounds," Narasimhan explained. "But we are designing this camera to be a microphone by imaging tiny vibrations invisible to the naked eye or ordinary cameras, and we can measure these extremely tiny vibrations." It's the kind of system that could, for example, record a rock show at a club, and from the morass of sound separate and channel each individual instrument into its own audio track for mixing. "For the first time, we were able to capture sound from different directions with a single camera, a single imaging system," Narasimhan said.

Despite the myriad applications already in development, Hebert said this is just the beginning. "There's a whole universe of other possibilities, in manufacturing, materials science and medicine, where we could apply some of the techniques we've developed in traditional computer vision to move things forward." Jeni sees digital health in particular as an area with enormous potential. "I'd like to see this technology really make a difference in clinical outcomes and change peoples' lives," he said. "I think we're getting there. The technology works great in lab conditions, but we need to take it out into the real world."

"At Carnegie Mellon, we have a long history of work on every aspect of computer vision: theory, software and hardware," said Kanade. "There are many pieces of specialized hardware that we've designed and built, and a lot of them have become very popular, like 3D cameras that use stereo vision to analyze depth in real time. We built that in the '90s," he recounted. "We have a great record of innovation, and it's not an overstatement to say that on computer vision research going back 30 or 40 years, we are the largest, most advanced computer vision institution."

Narasimhan echoed the pushing forward, building on the foundations of those who have gone before. "What we are about now," he said, "is creating the cameras of the future." ROBOTS ASSISTING HUMANS

Manuela Veloso walks with students and a co-bot through the halls of SCS.

HALEY R. MOORE

Eye-Gaze and Haptics: How Robots Learn to Interact and Assist Humans

From robotic vacuum cleaners to robots that deliver packages and meals to our doorstep, we are just beginning to grow accustomed to a world where we interact with robots in our daily lives.

> Researchers from the Robotics Institute have long been at work on robots that help humans with daily tasks. From soft robotics to medical and surgical robotics, and even robots that can make a pizza, the School of Computer Science continues to build on its foundations to develop robots to assist humans.

However, implementing robots when human beings might be sick, vulnerable or at their most fragile comes with a significant amount of precision, detail and care. Compounding the problem is the fact that human behavior is inconsistent and varies a great deal from person to person. Neither humans nor robots are infallible, which complicates studying the relationship between the two.

The Dynamics of Interaction

Henny Admoni, director of the Human and Robotics Partners Lab (HARP), shares this simple goal — to better understand and develop assistive robots that improve the quality of human lives.

Though assistive robots in the home are a relatively recent phenomenon, the idea is not new. Admoni recalled the 1960's era cartoon "The Jetsons" as an example of assistive robots entering human imagination and our desire to connect and interact with thinking machines. The robots on "The Jetsons" not only helped the family with menial tasks around the house, but they also had personalities and approached being members of the family.

Though the show aired 60 years ago, Admoni said it took until the early 2000s for technologies to begin to catch up. And it's important to note that assistive robots don't need to speak and be humanoid in their interactions for humans to develop relationships with them. Admoni pointed to the Roomba as an example.

"They aren't anthropomorphic at all — they are just discs on wheels," said Admoni. "People decorate them and if their machine breaks, they would want to repair it instead of getting a new one. So, people can form relationships with something that is very clearly a robotic machine."

Communicating with Eye-Gaze

The question becomes, how can we best communicate with robots that don't speak? Admoni's work in the HARP lab focuses on nonverbal communication and how robots can take advantage of key indicators to allow humans and robots to form better bonds. To overcome this, Admoni's lab uses eye-gaze technology to enhance human interaction. Using cameras and sensors to interpret and respond to the direction of a person's gaze enables the robot with more natural and intuitive communication and assistance.

HARP lab researchers developed a functional eye-gaze model, but the problem of inconsistent human movement, even in how they use their eyes, creates confusion in the model. To complicate matters further, most people use their peripheral vision to complete their understanding of their environment. Peripheral vision is tough for eye-gaze to track.

When beginning a new task such as reaching for an object, the gaze of a person's eye often switches to the next task before finishing the task of picking up the object. When people begin to multitask, the direction of their gaze becomes unpredictable to the model and can provide extra hurdles in tracking research patterns.

"I think we use eye-gaze as a really rich signal, but it's also a really noisy signal," Admoni said. "It's a challenge because we use it for so many different things — like to be aware of the world around us or to have social interactions and manage conversations."

Admoni said the way to know more about what's to come for human-robot interaction is to keep amplifying the research.

"If we think about robots and humans together, we are going to be much more successful — for a variety of reasons than if we try to separate the robots from the humans," she said. "Human-robot interaction as a community is the most important kind of recent evolution of robotics." ■



Co-Bots

Under the direction of Manuela Veloso, the Herbert A. Simon University Professor Emerita, the School of Computer Science pioneered the field of collaborative robots, or Co-bots, that work together with humans rather than perform tasks in isolation.

Throughout the '80s and '90s, SCS researchers delved into robotic manipulation and interaction with the goal of enabling robots to perform tasks in unstructured environments alongside humans. This research laid the groundwork for co-operative robots.

Integrating advanced sensor technologies and sophisticated control algorithms has allowed for greater perception and the ability to adapt to surroundings in real time, a crucial aspect of effective collaboration for co-bots. By the 2000s, Veloso actively explored human-robot collaboration, designing co-bots not only to perform physical tasks but also to interact intelligently with human collaborators.

CMU's approach to co-bots has been inherently interdisciplinary, and researchers across the departments of SCS and the university contributed to the design and development of new robotic platforms geared toward collaborative tasks. These platforms have combined mobility, manipulation capabilities and safety features to ensure effective interaction. Collaborations among computer scientists, engineers, cognitive scientists and social scientists have led to a comprehensive understanding of how robots and humans can effectively work together.

Co-bot research in SCS continues, keeping CMU as a hub for advancements in machine learning, natural language processing, computer vision and haptic feedback that enhance co-bot capabilities.

Director of the HARF

Lab and Assistant Professor in RI



Haptics for Health Care

Beyond the act of getting dressed, Assistant Professor in RI Zackory Erickson's lab focuses on other activities of daily living, which include tasks like eating and other functions we take for granted, but which are necessary for survival. Using cameras alone isn't enough, so his students use haptics, or the perception of touch in nonverbal communication between humans and sensory devices.

Haptic guidance and predictive control help monitor and record human-computer interactions. Sensors mimic force and motion that allows experts to dive deeper into the physical relationship of human-robot interaction. At the core of the research is the idea of keeping humans safe during all interactions. And there's more work to be done before they are ready for widespread use.

"It's still a research system, so we're still looking at how robots can leverage this knowledge and information," Erickson said. "And there is definitely a need to understand the use of haptics to guide the robot's motion to inform its interactions."

THE LINK

STACEY FEDEROFF

CMU Robot Puts on Shirts One Sleeve at a Time

Robotic-Assisted Dressing System Accommodates Different Poses, Body Types and Garments

Researchers in the School of Computer Science have developed a robotic system that helps humans dress and accommodates various body shapes, arm poses and clothing selections.

Most people take getting dressed for granted. But data from the National Center for Health Statistics reveals that 92% of nursing facility residents and at-home care patients require assistance with dressing.

Researchers in the Robotics Institute (RI) see a future where robots can help with this need and are working to make it possible.

"Remarkably, existing endeavors in robot-assisted dressing have primarily assumed dressing with a limited range of arm poses and with a single fixed garment, like a hospital gown," said Yufei Wang, an RI Ph.D. student working on a robot-assisted dressing system. "Developing a general system to address the diverse range of everyday clothing and varying motor function capabilities is our overarching objective. We also want to extend the system to individuals with different levels of constrained arm movement."

The robot-assisted dressing system leverages the capabilities of artificial intelligence to accommodate various human body shapes, arm poses and clothing selections. The team's research used reinforcement learning — rewards for accomplishing certain tasks — to achieve this. Specifically, the researchers gave the robot a positive reward each time it properly placed a garment further along a person's arm. Through continued reinforcement, they increased the system's learned-dressing strategy success rate. The researchers used a simulation to teach the robot how to manipulate clothing and dress people. The team had to carefully deal with the properties of the clothing material when transferring the strategy learned in simulation to the real world.

"In the simulation phase, we employ deliberately randomized diverse clothing properties to guide the robot's learned dressing strategy to encompass a broad spectrum of material attributes," said Zhanyi Sun, an RI master's student who also worked on the project. "We hope the randomly varied clothing properties in simulation encapsulate the garments' property in the real world, so the dressing strategy learned in simulation environments can be seamlessly transferred to the real world."

The RI team evaluated the robotic dressing system in a human study with 510 dressing trials across 17 participants with different body shapes, arm poses and five different garments. For most participants, the system was able to fully pull the sleeve of each garment onto their arm. When averaged over all test cases, the system dressed 86% of the length of the participants' arms.

The researchers had to consider several challenges

when designing their system. First, clothes are deformable in nature, making it difficult for the robot to perceive the full garment and predict where and how it will move.

"Clothes are different from rigid objects that enable state estimation, so we have to use a high-dimensional representation for deformable objects to allow the robot to perceive the current state of the clothes and how they interact with the human's arm," Wang said. "The representation we use is called a segmented point cloud. It represents the visible parts of the clothes as a set of points."

Safe human-robot interaction was also crucial. It was important that the robot avoid both applying excessive force to the human arm and any other actions that could cause discomfort or compromise the individual's safety. To mitigate these risks, the team rewarded the robot for gentle conduct.

Future research could head in several directions. For example, the team wants to expand the capabilities of the current system by enabling it to put a jacket on both of a person's arms or to pull a T-shirt over their head. Both tasks require more complex design and execution. The team also hopes to adapt to the human's arm movements during the dressing process and to explore more advanced robot manipulation skills such as buttoning or zipping.

As the work progresses, the researchers intend to perform observational studies within nursing facilities to gain insight into the diverse needs of individuals and improvements that need to be made to their current assistive dressing system.

Wang and Sun recently presented their research, "One Policy To Dress Them All: Learning To Dress People With Diverse Poses and Garments," at the Robotics: Science and Systems conference. The students are advised by Zackory Erickson, assistant professor in the RI and head of the Robotic Caregiving and Human Interaction (RCHI) Lab; and David Held, associate professor in the RI leading the Robots Perceiving And Doing (RPAD) research group.



Zackory Erickson, Assistant Professor in RI

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From Dreams toZOOMS

KEVIN O'CONNELL

The Journey of Alex Waibel and Rise of Natural Language Recognition and Translation

A swe were about to begin our interview, **Alex Waibel** placed two phones on the table — his own, and one to send a recording to a student who will perform a different type of language translation process.

He also set his laptop on the table, opened a Zoom meeting with no online participants and set it to record just the two of us. He helped invent the translation software in Zoom, so what better tool to use for our interview?

We have entered a new era of natural language recognition and processing. **But how did we get here?**

Foundations of The Language Technologies Institute

The foundations of the Language Technologies Institute date back to Raj Reddy, the Moza Bint Nasser University Professor of Computer Science and Robotics and former dean of SCS, and his work on the Harpy translation system for DARPA's Speech Understanding Research program. Harpy could understand over 1,100 words, roughly the vocabulary of a typical three-year-old.

Building on its CMU predecessors, the Dragon system came next. Dragon searched all possible syntactic and acoustic paths to

An Overnight Success Story 45 Years in the Making

When a new technology bursts onto the scene and seems to change our

lives overnight, it's often the culmination of dedication and years of hard work by countless people.

"Something becomes revolutionary when it reaches a level of performance and ease of use, when it's suddenly in the hands of everyone," said Waibel, Professor of Computer Science at CMU, and the Karlsruhe Institute of Technology in Germany.

Language translation — from instant transcription of Zoom meetings to the ability to produce a video, making someone speak in any language you prefer — now surrounds us. With new technologies come the serious questions of how to use them for their intended purpose and how to avoid the problem of misappropriation for any nefarious purposes.

determine an intended word. Next came the HERESAY-I system, which used a best-first strategy, revolutionizing the field by using a heuristic Beam Search

> algorithm which increased both the speed and accuracy of recognition.

With the goal of all people being able to freely communicate without language restriction, Jaime Carbonell, the Allen Newell Professor of Computer Science, founded the Center for Machine Translation in SCS in 1985, which became the Language Technologies Institute (LTI) in 1996. Carbonell directed the LTI until his death in 2020. Since its founding, the LTI has been the largest and most renown entity of its kind, leading the field in natural language processing, question-answering systems, and speech recognition and synthesis.

Throughout his career, Waibel has shared a similar path as Carbonell. Both have worked to build machines that will allow anyone on the planet to talk to anyone else without the barrier of language. "When I started, that was crazy," said Waibel. "Early on, people just shook their heads. So, it took 40 years, but you know, here we are. It's actually possible. And it's amazing how good it is."

Waibel admits that although it may feel like a switch turns and the world changes overnight, the reality of technology development is far more incremental. It takes years and years of effort by many people to achieve the incremental improvement necessary to provide a transformative technology.



Jaime Carbonell, Founder and Director of CMU's Language Technologies Institute

THE LINK:



YOU WANT TO LEAVE THIS PLANET WITH SOMETHING THAT **TOUCHES PEOPLES'** LIVES.

- ALEX WAIBEL

The Journey

Growing up in Barcelona and traveling the world, Waibel often faced language issues and awkward cultural situations. When he came to the U.S. to study at the Massachusetts Institute of Technology in 1976, he was interested in space and quantum physics, but he also had an engineering mind and wanted to combine his proficiency in science with his desire to solve problems from a humanitarian perspective.

"You want to leave this planet with something that touches peoples' lives," he said.

He found the human connection he sought in a group working on speech synthesis, with the goal of building machines that could read unrestricted texts. All in a technologicially limited world nearly unimaginable to today's SCS undergraduate students. No email. No smart phones. No screens of any kind.

"In my first programming course we used punch cards," Waibel said.

In his final year as an undergraduate, he told his advisor of his idea to build a machine you speak into that could translate the speech and repeat it back in another language. The advisor gave Waibel a look suggesting his idea might be a little far-fetched.

"He was, luckily, very polite," said Waibel, "and told me 'That sounds like a wonderful idea, Alex.'"

THE LINK

Raj Reddy and Harpy

Among myriad foundational developments for which Raj Reddy built the ground floor, was his work on natural speech processing. The development of the Harpy speech recognition system, pioneered by Reddy, the Moza Bint Nasser University Professor of Computer Science, revolutionized the field. Throughout the late 1970s and early 1980s, Reddy and team set out to develop a speech recognition system capable of understanding continuous, natural language input. The result was Harpy, a research project whose influence on the field of speech recognition can still be felt today.

- The Harpy system was one of the early adopters of Hidden Markov Models (HMMs). HMMs have since become a foundational technique in many speech recognition systems, such as Google's DeepSpeech and Apple's Siri in their earlier iterations.
- Harpy introduced the concept of language modeling, which considers the likelihood of word sequences, thereby improving natural language accuracy. Contemporary systems often use advanced language models such as neural networks to enhance speech recognition accuracy.
- The Harpy system utilized acoustic modeling, or the capturing statistical properties of speech sounds. Today's voice assistants and automatic transcription services rely on sophisticated acoustic models that evolved from the concepts developed in Harpy.
- The decoding algorithms and search strategies employed by the Harpy system for finding the most likely word sequences in speech data have influenced the development of modern algorithms used in large-vocabulary continuous speech recognition (LVCSR) systems.
- The Harpy system was able to adapt to different speakers by making use of training techniques, laying the groundwork for speaker adaptation and personalized voice recognition in today's systems. Amazon Alexa and Google Assistant allow users to train their devices for better recognition.

After Harpy, companies like IBM, Microsoft, Google and Apple saw tremendous potential and invested heavily in speech recognition technology, creating products like IBM Watson, Microsoft Azure Speech Service, Google Speech-to-Text and Siri.

Reddy's work demonstrated the feasibility of automatic speech recognition systems. Harpy could understand and transcribe spoken language, helping pave the way for subsequent developments and enabling their integration into everyday applications and making it an integral part of human-computer interaction.

When it came time to decide what to do next for graduate studies, Waibel heard about Carnegie Mellon, where some of the world's best researchers were working on speech recognition. This was about the same time Reddy was working on the Harpy Speech Recognition System.

"I said [to Reddy] I'm here from MIT. And he said, 'Can you stay here and start working now?' And I said, 'Yes, I could.'"

But still, few people believed that speech translation was possible. Waibel's dream of making a communication machine, a mediator that could help people talk to other people in a different language, required three separate technologies that could work together: the synthesis to speak it out loud, the translation to go from one language to another, and the speech recognition technology to make it understand speech and convert it to text.

So Waibel began work on the third problem first. But which approach to take?

There was early work by Herb Simon and Allen Newell that suggested the best approach to solve recognition might be via search. But Waibel and his collaborators quickly realized that there were far too many ways to say things — each with their own nuance — and that human speech itself is often ambiguous.

Reddy provided another possible avenue with his work on early systems of knowledge modules. This knowledge-based approach to speech meant trying to do everything by the rules of speech. Getting in the way of this were issues with acoustic and noise variations. Finally, Waibel decided to throw out the rules.

"We needed something that learns like humans learn," he said. "A human cannot explain how they learn. They just learn."

For a moment he thought machine learning might provide the answer, but machine learning was still in its infancy at the time.

The next attempt was a statistical approach. Waibel worked with Kai-Fu Lee on what he called a "secret project" where they started with statistics and worked toward a fixed system. To Waibel, the statistical approach still seemed too shallow to be successful.





- RAI REDDY

"I felt there needed to be a way of learning more of the abstract knowledge within it," said Waibel.

It was at this time when Geoffrey **Hinton** came to Carnegie Mellon and introduced Waibel to his work with backpropagation. The backpropagation neural network training algorithm is capable of adjusting the model's internal parameters by calculating the degree of the errors it makes, thus enabling the model to learn and improve its predictions over time.

So, the only missing piece was machine translation. Waibel admits that here, he was fortunate once again. In 1986, a visiting researcher to CMU from Japan told Waibel they were opening a large laboratory in Japan called the Advanced Center **Communication Research Lab** (ACRL), where they were working on machine translation. Japan had funding for innovative projects at that time and they wanted to prove their innovative power, Waibel noted.

> "That's it," he thought. "Here was my chance to actually work on this third element of the vision."



Geoffrey Hinton, Turing Winner

He continued to partner with Geoffrey Hinton, which resulted in their inventing the time-delay neural network (TDNN), a network that was able to classify a pattern and shift the classifier invariantly, solving the long-standing problem of how and where to shift the classifier. It was key because natural speech flows continuously. The break classifiers was that they could not recognize the same pattern after the shift.

It was still the late 1980s and with computing power as it was at the time, few large scale advances took place because the neural networks than the statistical systems that Kai-Fu Lee was having success with.

"We were always stuck by not being able to compute more," said Waibel.

It wasn't until improved computing power of the 2010s that Microsoft, very active in the early models, began showing renewed interest. Using much the same models that Waibel and his colleagues had developed years earlier, their demos suddenly began to show performance improvements — up to 30% improvement. Waibel and his colleagues were surprised and intrigued.

"We now know if you stack deep neural networks on top, they get better and better ... and you get better results," said Waibel.

After returning to CMU from Japan, Waibel started a neural network speech group. By combining machine translation techniques, some knowledgebased techniques, and some programmed approaches with the learned approaches, the team developed their first working speech translation system in 1991, known as the Carnegie Mellon Translation System.

CMU held a press conference, linking labs in Germany with colleagues in Japan, and presented the first video conference with speech translation, where spoken English was translated into spoken Japanese. There was widespread media interest, including the New York Times and CNN.

WE WERE ALWAYS STUCK " **BY NOT BEING ABLE TO COMPUTE MORE.**

- ALEX WAIBEL

"It was a bit of a sensation," said Waibel. "But we could only do 500 words." And the vocabulary was limited to a single domain. If the domain was computer science, the system would not understand any terms in astrophysics. They continued work to break down barriers between restricted domains. The proof came in being able to translate an entire lecture.

In 2005, Waibel and his colleagues successfully put together an unrestricted vocabulary speech recognizer and an open domain machine translation system. They continued working to get the latency in the recognition time down before they felt ready. Once that had been achieved, they held a worldwide press conference at CMU demonstrating an automatic lecture translation system where they verbalized a lecture into the speech recognizer in English; it recognized and translated it into Spanish.

Waibel's focus then shifted to make the system available to the public. About this time the iPhone 3GS had come out, as well as the development of the App Store. Waibel knew that the phone had the computing power to put the technology of speech recognition and translation into people's hands.

The result was that Waibel and his partners founded Jibbigo in 2009 and made it available. One of the key advantages was that the app worked without the need for an internet connection, which meant that travelers could use it anywhere. The company was eventually acquired by Facebook in 2013. So Waibel left CMU once again for a new adventure. He returned two years later to continue his work on simultaneous translation and to solve the challenges presented by larger vocabularies, the need for systems to be faster and to decrease latency times.

Then, the president of the German university Karlsruhe Institute of Technology (KIT,) asked Waibel to help solve the problem of attracting international students who didn't want to learn German. Waibel worked on the German version of the lecture translator. The success and press garnered by the project led to other universities to knock on Waibel's door. Then the secretary general of the European Parliament wanted a system.

The requests kept Waibel's team busy, but there came a point where he knew they couldn't do it all from a university lab. Waibel was hesitant to begin vet another company, this being his 11th, so he handed the reins to Sebastian Stuker, a team member, to found KITES. Waibel funded and advised Stuker.

Then came the pandemic.

Zoom became aware of what they'd been working on and with the need for teaching and essentially all meetings to be online, after a year's courtship, Zoom bought KITES.

"If you see subtitles on Zoom and translation," said Waibel, "the seed of the team that does it is our team in Karlsruhe."

66 **IT'S NOT ONLY VOICE.**

IT'S MULTIMODAL. - ALEX WAIBEL research fellow at Zoom. He's still at work on the recognition of highly technical terms and their acronyms, which has improved recently.

A current challenge that excites Waibel is multi-linguality, or the use of different languages in the same sentence. Switching languages mid-sentence causes systems that have trouble recognizing the language mode in which they should be running to recognize the speech and how to translate it.

"You have a German lecture in computer science that's peppered with English words," said Waibel, "and sometimes people switch to English when they want to say something. People come up with weird ways of speaking, but everyone may understand what they mean because they know some English. And it's even considered cool for young people in Germany to use a lot of English words in their German."

Waibel's goal all along has been to allow one person to understand another person in another culture with no barriers of any kind. He still strives to allow people to be able to communicate and interact with one another freely. But fully free communication goes beyond mere words.

"It's not only voice, it's multimodal," he said.

Waibel's work continues as a

Toward Language Transparency

Hand gestures, facial expressions and cultural affectations create noise and miscommunication not inherent in the words themselves. To address this, Waibel works on translating as much multimodal communication as possible.

> One area of focus for Waibel is the area of automatic dubbing of videos. This technology takes the translation of video in other languages to the next level by making use of the speaker's own voice. Al alters the video to make the speaker appear to be speaking the new language translation.

> The result is called a "lipsynchronous" video, because the speaker's mouth moves convincingly along with the translated language. A few obvious applications are movie dubbing (no subtitles to read) as well as global video conferencing.

Waibel remains aware of the threats posed by so-called deep fakes, or the use of these types of technologies to misrepresent the truth, and thereby mislead people. He's working on solutions for safeguarding people from potential threats — a much larger topic for another article.

Waibel believes we have moved beyond the term language translation. He now prefers to call his work language transparency.

The name — and certainly the technology — may change, but Waibel's goals of fluid and comfortable communication, without barriers, remain the same.

FROM MILLVALE TO MOSCOW:

Rote Blazes Trails for Women in STEM

SUSIE CRIBBS

Patti Rote came of age in the small borough of Millvale, just north of Pittsburgh. Her working-class family never had a car, and she clearly remembers walking "halfway to town" to hop a bus into the city. Yet decades later, the founder of Girls of Steel in Carnegie Mellon University's Robotics Institute has traveled from Millvale to Moscow and everywhere in between, breaking barriers for herself and the generations coming up behind her. Patti Rote pictured with CHIMP, the CMU Highly Intelligent Mobile Platform robot.

Rote, who has done everything from helping tech companies grow to training high school students to build robots, retired earlier this year after a career fueled by grit and an adventurous spirit.

Although she came from a low-income family, Rote attended Catholic schools on scholarships and graduated from Millvale's Mt. Alvernia High School before taking a job with the H.J. Heinz Company. After a short time, she found a new home at another Pittsburgh institution, Westinghouse. The company paid for her bachelor's degree in business from the University of Pittsburgh, and, after its acquisition of CBS in the 1990s, supported her MBA work at Duquesne University.

Rote notes that she "grew up" with Westinghouse. But it's also where she started breaking gender barriers. Westinghouse began a trading company during her tenure, and Rote was a buyer on the team.

"Every Monday morning the buyers had a meeting," Rote said. "And my boss said, 'I need someone to go to the Soviet Union, make a couple stops in Taiwan, and circle back and end up in Brazil. Do I have any takers?' I looked around. Nobody raised their hand. So I did. And I thought to myself, 'I don't know what I just did, but what the heck?""

That "what the heck?" outlook launched her into two decades of international travel, mostly to Russia, Asia and countries throughout South America, researching topics like why young people didn't listen to American music in their cars. Though she spoke none of the local languages, she was drilled on cultural protocol, which she says was far more important. She always traveled solo — and was often the only woman in her field doing so.



After about 20 years of globetrotting, Rote became a consultant and began working with Tim McNulty, then an associate provost at CMU and now associate vice president for Government Relations. Her job? Regularly travel to Capitol Hill, know the hot robotics issues in each congressional district and give presentations on those topics to congressional staff. In less than three years she delivered 200 presentations and became intimately acquainted with technical companies — especially in robotics.

But how did she start helping kids build robots through Girls of Steel?

"I used to judge robotics competitions just because I liked technology," she said. "I did that for three years straight, and every time I came back home to my husband and I said, 'I can't believe this. Where are the girls? They could do this if they had the right mentorship!' And he said, 'Quit complaining and go do something about it."" So she did.

Still in her consultant role, Rote met with William "Red" Whittaker, Founders University Professor in the Robotics Institute and director of the Field Robotics Center. She pitched the

I CAN'T BELIEVE THIS. WHERE ARE THE GIRLS? THEY COULD DO THIS IF THEY HAD THE RIGHT MENTORSHIP!

- PATTI ROTE, FOUNDER OF GIRLS OF STEEL IN RI

FALL 2023

WE HAD NOTHING. WE DIDN'T EVEN HAVE PENCILS. SO I THOUGHT TO MYSELF, 'HOW AM I GOING TO JUMPSTART THIS?'

— PATTI ROTE

idea of fielding a primarily female team in the FIRST Robotics Competition, an international program that prepares young people for the future through inclusive, team-based robotics programs. Whittaker liked the idea.

"He said, 'Go find me 25 girls and \$25,000 and you got a deal," Rote said.

She got to work, getting most of the initial funds from the Grable Foundation. But Girls of Steel was so important to her that she threw in her own money, too.

"We had nothing. We didn't even have pencils. So I thought to myself, 'How am I going to jumpstart this? I should at least throw in a thousand dollars so someone really believes that I want to do this," Rote said. "I would never start a program, say 'this is a great idea,' throw it over the wall and hope it happens."

For that first Girls of Steel cohort, Rote recruited from CMU neighbors the Ellis School and Oakland Catholic. With funding and participants locked down, all she needed was a roboticist to take the technical reins. She found that in George Kantor, research professor and associate director of education in the Robotics Institute.

Together, Rote and Kantor co-led Girls of Steel for more than a decade. Rote eventually joined the CMU staff part time, and Girls of Steel expanded its offerings to include programming for both middle and elementary school students. After 14 seasons of growth and countless successes, Kantor recently relinquished some of his role to former Girl of Steel Liz Kissell. Similarly, Rote realized that the organization was in good hands. She trained parents to fundraise and keep the business end of things in shape. She has the right mentors in place to motivate the team and move it forward. So she retired in June of 2023.

Rote's contributions to CMU, Pittsburgh and the larger technical community go well beyond Girls of Steel. She led CMU's participation in the National Defense University for years, and recently helped launch a first-of-its-kind program, AI for Teachers, that brings high school educators from across the country to CMU for a week of training from artificial intelligence experts Stephanie Rosenthal and Pat Virtue. She's tirelessly fundraised to turn ideas for improving STEM education into a reality and helped transfer countless technologies to the public sector.

Rote notes that she "hates being at home," which should surprise no one, so retirement won't mean a life of leisure. She still plans to volunteer with Girls of Steel during their busy months. And while she's had enough of international travel, she hopes to spend more time in one of her favorite places, Nantucket, Mass.

In typical fashion, though, she can't leave a good cause alone.

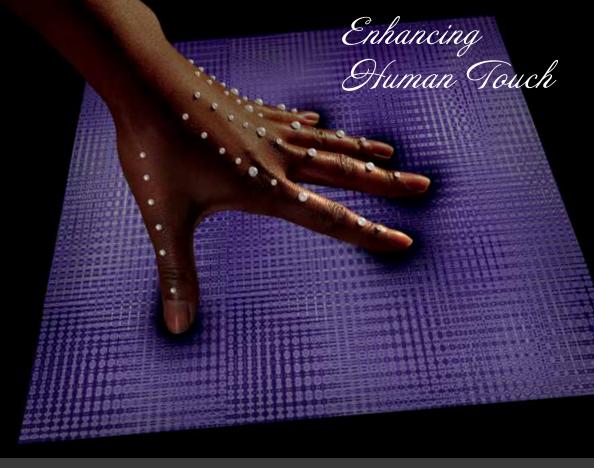
"I have to be doing something all the time. And people that know me are worried about that," said Rote, who now lives in Pittsburgh's Bloomfield neighborhood. "I love tennis, and the Frick Park courts in Pittsburgh need to be redone, and the building needs updates. A good friend asked me if I wanted to give a hand, so that's on the horizon."

"

I WANT TO HELP. I LIKE TO HELP PEOPLE. WHETHER IT'S KIDS — THE TEENAGERS THAT YOU HOPE GET ON THE RIGHT PATH — OR RESEARCHERS. — PATTI ROTE

Looking back on her time at CMU, Rote fondly reflects on what inspired her each day.

"It's a compilation of things. It's meeting scientists. They're unbelievable. But it's also realizing where people like me, who are not scientists, need to help them," Rote said. "I want to help. I like to help people. Whether it's kids — the teenagers that you hope get on the right path — or researchers. And you can do that easily at CMU."



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First-year CSD students completing a JEDI breathing exercise

Creating a JEDI Mindset

STUDENT-CREATED COURSE SHARPENS FOCUS ON DIVERSITY, EQUITY AND INCLUSION IN THE COMPUTER SCIENCE COMMUNITY

STACEY FEDEROFF

o begin class, student facilitator **Ananya Joshi** asks the room of first-year Ph.D. students to stand if they are comfortable doing so. Then, she plays a short video leading students in light stretching and a breathing exercise. Soothing music chimes as the students stretch from side to side, then, prompted by the woman in the video, they all take a deep breath in and out together.

"All right, that was our centering practice," says Joshi before reviewing the agenda for the second week of CS-JEDI: Introduction to Justice, Equity, Diversity and Inclusion in Computer Science.

First conceived of in 2020, the six-week course — now required for all first-year
Ph.D. students in SCS's Computer Science Department — aims to create a more
welcoming computer science community. CS-JEDI was primarily developed by CS
Ph.D. students who, after investing more than 1,300 hours of work, received the
university's Graduate Student Service Award in 2022. CS-JEDI is now also the
subject of published research, which won a best paper award at the Special
Interest Group on Computer Science Education (SIGCSE) conference, held
in March 2023. Now, in addition to continuing to educate first-year CSD
students, the program may spread not only to other departments within
SCS, but to other universities as well.

"[CS-JEDI] opens the door to deeper conversations and allows students not only to learn, but also to understand the importance of what they can do and how they can contribute to this whole environment of diversity, equity and inclusion," said **Darla Coleman**, executive director of SCS Diversity, Equity & Inclusion Initiatives.

> When student facilitator **Victor Akinwande** participated in the class as a new international student from Nigeria, he said he found not only the discussion valuable, but also the curated resources available in an online library that any SCS graduate student can access and utilize.

"It was just super helpful to be aware of and be exposed to these topics," Akinwande said.

THE LINK

THE LINK

They approach it through one of several sub-topics called lenses, which are then discussed with a synthesis group of four to five students.

When she first participated in CS-JEDI as a student, Joshi said the discussion groups built into the curriculum allowed her to connect with her fellow Ph.D. students in ways that she wouldn't have otherwise. Students also found the discussion topics apply to their academic work. "Some of the students talked every week about how the class topic was helping them get a better idea of their own research," said Joshi.

BEGINNING WITH CORE QUESTIONS

Zico Kolter, associate professor of computer science and faculty instructor for the CS-JEDI course, described how practitioners of technical fields like computer science often believe they are dealing in objective truths, and this may inadequately account for the fact that everyone sees the truth through their own lens. The CS-JEDI class allows students to consider the ways societal norms may influence their perception of the truth at the onset of their research careers.

important perspective for students to see."

"That's a new notion for a lot of people in science as a whole," Kolter said. "And I would say most scientific programs don't touch on them at all ... so bringing them up is an extremely



Bailey Flanigan, Ph.D. student and co-founder of JEDI "The set of Ph.D. students, staff and faculty who

contributed to the curriculum approached it from

a diversity of perspectives and experiences around

DEI topics," Flanigan said. "This was important in

of our community might experience the material.

Another main goal we had was to tailor the content

to the computer science Ph.D. experience, since this

After running an official course pilot in Spring 2021,

the faculty of the CSD officially added CS-JEDI to

the Ph.D. curriculum, making it a requirement for

all first-year Ph.D. students. The proposal to make

the course required for all students was discussed

extensively, but ultimately approved in the interest

of more evenly redistributing the work of creating

"We designed CS-JEDI to be a required class because

making our community welcoming to all requires

everyone — not just those who are most affected

by DEI issues, or those who are already interested in

DEI — to self-educate and engage with these topics,"

really valuable for Ph.D. students in general, helping

said Flanigan. "Fluency in DEI topics can also be

them to be more connected to their community,

and to be more effective collaborators, teachers,

mentors and job applicants."

an inclusive environment, Flanigan said.

is an experience that all CS-JEDI students all have

in common."

helping us anticipate how different members

A discussion in June 2020 among Ph.D. students Bailey Flanigan, Catalina Vajiac and Sara McAllister planted the seeds of what would eventually become the CS-JEDI course. The three talked about their experiences as women in computer science, and how their interactions as Ph.D. students left them feeling like something was missing.

"Before that conversation, we all felt like we were trying to overcome the same set of issues alone," said McAllister. "And although we weren't sure what a concrete solution would look like, we wanted to see if our peers were having the same experiences."

The three informally surveyed their peers and found similar anecdotes. "Some students talked about keeping their struggles to themselves because they didn't want to be perceived as a burden to their advisors or other people," Flanigan said. "It seemed like there were no real channels for students to have honest conversations about the difficult issues — DEI-related or not — that tend to come up in Ph.D. programs."

The CS-JEDI course emerged as a step toward addressing that problem, by offering a space where students could have open and evidence-based discussions about DEI in academia and computer science. After the CSD Departmental Review Committee gave the green light to pilot the course, 15 SCS Ph.D. students worked together in close collaboration with the Eberly Center for Teaching Excellence & Educational Innovation to design the CS-JEDI curriculum and included curriculum reviews.

What are these words we use to describe identity

FALL 2023

COURSE CONNECTIONS

Each week, CS-JEDI students hear from guest speakers on the current week's topic from within the CMU community. In the second week of class, guest speakers Jordan Taylor and Adinawa Adjagbodjou — both Ph.D. students in the Human-Computer Interaction Institute — presented on how biases of identity, intersectionality and systemic inequality affect research and teaching, and their particular importance to Ph.D. students. Taylor broke down how research survey design can be affected by stereotype threat, which is the risk of confirming negative stereotypes, depending on how questions are worded or organized.

"This is something that is so foundational, since we make Google Forms all the time, be it for recruiting students or to evaluate something," said Taylor. In another example, Taylor pointed out how something as common as the name for the "stable marriage" problem, a canonical problem in computer science and economics, could alienate LGBTQ+ people.

"The formulation of this problem as a marriage between a man and a woman can be marginalizing if you're a queer person in this class and that's not how you imagine yourself navigating the world," said Taylor. "There's a way you can do these problems and instead design alternative structures."

During each of the six class sessions, all structured around collaborative learning, students study a core question.

Presenters Jordan Taylor (left) and Adinawa Adjagbodjou (right), Ph.D. students in HCII, speaking about how biases of identity, intersectionality and systemic inequality affect research and teaching for Ph.D. students.

First-year CSD students listening to JEDI guest speakers before forming discussion groups

SHIFTING THE CULTURE

Two more curriculum overhauls later, different versions of the class have now been held four times, first on Zoom and now in person.

The program's success wouldn't have been possible without the collaborations among the leadership team, students and faculty in CSD.

"When I started this endeavor with Bailey and Catalina," said Sara McAllister, "I had no idea what the reaction would be, but the support I've received around it from my peers, my advisors, my collaborators and others has been amazing."

According to the published research on CS-JEDI, about half of the students who were glad they took the course also said they probably wouldn't have taken it if it was optional.

"To me, this is a promising sign for required DEI education, because it looks like many students value the opportunity to learn this material ... and otherwise wouldn't get it," Flanigan said.

The article also reports that students most strongly agreed that CS-JEDI increased their awareness of their peers' perspectives, their ability to create inclusive environments, and to identify and bring up these topics and advocate for themselves.

"I've definitely heard more people talking about DEI issues just walking around the hallways or at Ph.D. events," said McAllister. "I hope that newer and future Ph.D. students feel more included and, as they go on in their careers as teachers, researchers, managers and mentors, are able to identify and remedy DEI issues."



Emma Strubell, an assistant professor in the Language Technologies Institute, believes initiatives like CS-JEDI not only educate students who hold privilege in certain ways, but also give marginalized students formal ways to frame what they're experiencing. Strubell expressed her wish that she had something like this course when she was a Ph.D. student.

"I think this is a great way of trying to shift the culture to a more positive space," Strubell said.

Last year, Strubell organized two mini-JEDI sessions based on and inspired by the material and philosophy of the full six-week course. Raising awareness around diversity, equity and inclusion issues for Ph.D. students who are pursuing careers in academia can improve the overall environment for future generations of students.

"I hope we can continue this momentum," Strubell said.

Adinawa Adjagbodjou discussing machine bias with students

Our goal is to create a sense of belonging for all students within SCS.

Diversity, Equity and Inclusion

LONGEVITY FOR BELONGING

Now that the course has been built and approved, the focus of the CS-JEDI project has shifted to its sustainability. To promote continuity of instructor expertise, the two student-facilitators co-teaching the course each semester are interleaved, so that one student instructor has always co-taught the course once prior. The curriculum also includes interchangeable elements at several levels of detail, so that the course can more easily adapt to student feedback.

Eventually, the CS-JEDI program could expand beyond CSD to accommodate all departments in SCS.

"I think a big part of what we've done so far is show that it's possible to teach a course like this," Flanigan said. "The fact that this course came from students and it's taught by students makes it unique. Also, the fact that we're actually teaching these topics in a required setting, and we're collecting detailed data that suggests that it's going well, gives precedent for similar initiatives to be adopted at other places."

Fielding interest outside Carnegie Mellon, Flanigan gave a presentation on this effort in February to similarly curious students at Columbia University.

"I see this as the beginning of many more schools hopefully doing something like this — and hopefully doing it even better," Flanigan said, "to the point where people across institutions are combining their knowledge and building up a community understanding of how to equip our students — and hopefully eventually, faculty — with tools and strategies for making our field inclusive." CS-JEDI fits in alongside other DEI programs available to all students within SCS, such as the student-run SCS4ALL or Women@SCS. The SCS DEI office also periodically hosts workshops on recognizing unconscious bias through a program called BiasBusters.

"Our goal is to create a sense of belonging for all students within SCS," Coleman said.

"The hope is that it has some longevity, and that it continues to do the good work that the CS-JEDI leadership team started."

CONTINUING THE JOURNEY

At the end of the presentation on stereotype threat, one student wanted to know how to best look for these biases, asking "Is there a list of examples to look through?"

Taylor responded that no, there isn't a list — and, essentially, that was the reason for the development of the CS-JEDI course in the first place. These issues can't be eradicated by simply checking off a list. Rather, recognizing them has to be the first step in the journey of understanding that leads to more innovative teams and ideas.

"Something to think about when there's a stereotype threat," Taylor told the student, "is an ethos of mindfulness, which is why it's important for us to talk about these issues of identity."

40

FALL 2023

The Takeo Kanade Endowed Professorship

IN AUGUST, CARNEGIE MELLON UNIVERSITY ANNOUNCED THE CREATION OF THE TAKEO KANADE PROFESSORSHIP, IN HONOR OF ONE OF THE GENUINE TRAILBLAZERS IN THE FIELD OF COMPUTER VISION.

CHRIS QUIRK

he professorship is the gift of a group of longtime friends and former students — Jing Xiao and Yu Li, Hongwen Kang, Yan Li and Chenyu Wu, Hua Zhong and Min Luo, Lie Gu and Yi Zhou, Mei Han and Wei Hua, Yanghai Tsin and Hongming Jin and Hang Su — who came together to find a meaningful way to celebrate Takeo Kanade's achievements. Their joint lead-gift for the Kanade Professorship recognizes the importance of Kanade's career and how he changed the course of their lives as a teacher and mentor.

Takeo is one of a few early pioneers in the fields of computer vision and robotics. — Martial Hebert, Dean of SCS

Takeo Kanade is the U.A. and Helen Whitaker University Professor of Computer Science and Robotics. Over the course of his career, Kanade invented, worked on or published some of the most important creations and theories of computer vision, and also developed unique robotic devices. "Takeo is one of a few early pioneers in the fields of computer vision and robotics. Over the past five decades, his foundational contributions have had a profound impact on further reaching fields of study and he has made seminal contributions in areas ranging from computer vision and autonomous vehicles to medical robotics," said Martial Hebert, dean of the School of

Computer Science. "He shaped the field of computer vision from its infancy in the 1970s to its current level of exponential growth. Within CMU, Takeo has been instrumental in transforming the Robotics Institute from a research center into a fullfledged academic department with graduate and undergraduate programs that are unique."

Born in Hyogo, Japan, Kanade earned his doctorate in electrical engineering from the Kyoto Institute. and then taught there for seven years. In 1980, he began his more than 40-year tenure at Carnegie Mellon. Kanade has won numerous awards for his work, including the prestigious Kyoto Prize for Advanced Technology, which recognizes those who have made significant contributions to the betterment of humanity. Kanade has also won the Bower Award and Prize for Achievement in Science from the Franklin Institute in 2008, and both the Okawa Prize and the ACM-AAAI Allen Newell Award in 2007.

In the 1970s, Kanade created one the first facial recognition systems, using a library of facial images he assembled that was likely the largest database of its kind at the time. In the 1980s, Kanade led a team of Carnegie Mellon researchers that developed NavLab, one of the earliest self-driving vehicles. Two Carnegie Mellon researchers took the vehicle 3,000 miles, from Pittsburgh to San Diego. NavLab drove more than 98% of the trip autonomously.

He shaped the field of computer vision from its infancy in the 1970s to its current level of exponential growth.

Kanade's most famous invention is EyeVision, which he designed and built for CBS to use during Super Bowl XXXV in 2001. For the broadcast, Kanade and his team mounted an array of cameras high up on Raymond James Stadium in Tampa, and designed a computer processing system that synthesized the inputs from the cameras into a smooth, flowing image that rotated the angle of the view of the play. Kanade appeared at halftime to explain the technology, and he may well be the only professor to appear on a Super Bowl broadcast. "Before EyeVision, when I got on a plane and talked to the person next to me during the flight, I'd tell them I was a professor at Carnegie Mellon working on robotics, and that was it," said Kanade. "But when I told people I built EyeVision, they were very interested to hear about it. EyeVision was a ticket to wonderful conversations with anybody in the world."

In 1981 Kanade discovered, along with his then-student Bruce Lucas, an algorithm that provided a new way to track objects visually, the Lucas-Kanade Method. "Bruce said we should publish it, but I told him no, you can't write a paper on this because it's based on the Taylor Expansion, which is 300-year-old math," Kanade said. Lucas placed the paper in the Proceedings of the 7th International Joint Conference on Artificial Intelligence. The Lucas-Kanade Method became a formative tool in the field, and the paper has garnered more than 18,000 citations. "It just goes to show you," said Kanade, laughing, "that if your professor tells

you not to publish something, you might want to publish it anyway."

At 78, Kanade is still a dynamo of energy for his work, and remains unceasingly curious. In a recent interview that went almost three full hours and ended well after midnight. Kanade recounted his achievements with his characteristic modest humor; expounded on the history of computer vision, epistemology and the future of technology; and, described future projects. He is now devising a multicamera technology using mobile phones so remote viewers could tour a spectacular site virtually, an idea he had when visiting the Taj Mahal. "It's a beautiful, unimaginable place. Everybody should visit, but it's not easy to get to," said Kanade.

We covered everything, from the theoretical to software to technology and hardware. Our versatility is probably our real forte, and I'm proud of that.

The Takeo Kanade Professorship will be a legacy not just to Kanade's remarkable career, but to the spirit and legacy of innovation that Kanade and his colleagues have created at the university. "I don't think it's an overstatement to say that the Carnegie Mellon Computer Vision group, for the last 40 years, has been the most advanced and influential," said Kanade. "We covered everything, from the theoretical to software to technology and hardware. Our versatility is probably our real forte, and I'm proud of that."

A LEGACY OF INNOVATION

GIVE TO THE **RAJ REDDY FUND FOR ARTIFICIAL INTELLIGENCE**

Raj Reddy's contributions to artificial intelligence cannot be overstated. As founding director of the Robotics Institute and a former dean of Carnegie Mellon University's School of Computer Science, he oversaw revolutionary developments in autonomous driving, computer vision and speech recognition (where he was personally a pioneer). The Raj Reddy Fund for Artificial Intelligence celebrates Raj's devotion to CMU, the School of Computer Science and AI in general.

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Jenny Belardi, Chief Advancement Officer, School of Computer Science 412-268-8810 ■ jbelardi@andrew.cmu.edu

> **Carnegie Mellon University** School of Computer Science

f 🕑 💿 in SCSatCMU

New LTI Director To Usher in 'Responsible Thinking' at CMU



AARON AUPPERLEE

Mona Diab understands what is at stake.

As a research scientist at two of the largest technology companies on the planet, Diab saw the impact innovations had as they spread across the globe. And with artificial intelligence poised to usher in the greatest technological leap since the internet, Diab wants to train, teach and prepare students, researchers, scientists and communities to think responsibly about these new tools.

We're living in a world of proliferating AI and generative AI. There is so much at stake." – Mona Diab, Director of LTI

"We're living in a world of proliferating Al and generative Al. There is so much at stake," Diab said. "We are at an inflection point for this technology and the discipline as a whole. It is a critical time to take into account its impact and sustainability."

Diab takes the reins of Carnegie Mellon University's Language Technologies Institute (LTI) this month. Part of CMU's School of Computer Science, the institute is home to cutting-edge research into the large language models powering the recent wave of generative AI systems and has a history of developing systems that have changed how computers understand and interact with humanity.

For Diab, AI researchers, scientists and students must consider issues ranging from security, privacy and accountability to diversity, equity and inclusion. They need to ask questions about climate and culture alongside questions about ones and zeros.

Responsible thinking needs to become core to our work. It should shape the future of language technologies and AI at large."

Diab coined this the "responsible thinking" approach, and she wants the LTI to embrace it as fully as critical and computational thinking.

"Responsible thinking needs to become core to our work. It should shape the future of language technologies and Al at large" Diab said.

Diab joins CMU from Meta, where she was the lead responsible AI scientist. Before Meta, Diab worked as a principal scientist at Amazon Web Services and was a professor at George Washington University, where she founded the CARE4Lang lab. She is a globally renowned expert on Arabic natural language processing (NLP), multilingual processing and computational social sciences. She earned a doctorate in computational linguistics from the University of Maryland and a master's degree in computer science from George Washington University.

She majored in computer science and Egyptology with undergraduate degrees from The American University and Helwan University, both in Cairo. Diab blends both of those majors in a research thrust using NLP technology to build tools to read and reconstruct hieroglyphics in hopes of opening the field to more people and gaining new insights into history.

CMU's trailblazing research, top AI and computer science programs, and talent drew Diab to the university. She said there is no better place to affect the development and use of the next generation of technology than the School of Computer Science.

R

Diab believes there is a gap in the current workforce, as it doesn't cater to what the current technology needs. To fill that gap, she wants to instigate a strong student-centric paradigm shift at CMU, to sustain excellence in both research and pedagogy. She aspires to train the best possible talent and transform the LTI into a leader in responsible thinking. With top faculty training top students who go on to secure top positions in industry and academia, the institute is positioned to snowball a responsible posture toward AI.

"Mona Diab's relentless pursuit of responsible AI in both academia and industry will strengthen the work of the Language Technologies Institute, School of Computer Science and Carnegie Mellon University as we seek to empower future generations of AI talent and develop a new wave of transformative technologies in an ethical, fair and sustainable manner," said Martial Hebert, dean of the School of Computer Science. "We are thrilled to have Mona's expertise and passion at CMU and excited to work with her on her vision."

Diab wants to proactively build the responsible Al framework into technology from the onset to avoid potential cultural harm as it spreads across the globe. She saw these harms as social media platforms spread to other countries, where Western-built platforms couldn't accommodate the nuances of different cultures.

Her work at Meta changed how the company handled Arabic, challenging the company to abandon the previous notion that it was a monolithic language and instead acknowledge the rich and diverse variants spoken around the world. That broader understanding helped Meta better grasp the language, leading to better translations, better identification of hate speech and a better user experience.

THE LINK

We must embed the technology with the right frameworks and build systems that are culturally aware and culturally responsible."

"I'm Muslim and I'm Arab, and I'm concerned that a lot of this technology is going to be adopted blindly," Diab said. "We must embed the technology with the right frameworks and build systems that are culturally aware and culturally responsible."

Diab advocates for computer scientists to work alongside social scientists. Anthropologists, sociologists, ethicists and others can help AI engineers think about problems from culturally different points of view and tune those systems to improve them. But this is not a one-way street. Diab believes that the relevant social sciences can also benefit from working with computer scientists.

Developing AI technology must also happen with the people it intends to serve, and feedback from that population should guide evaluations.

"It's in our interest to learn from them and assess the success of our systems with them," Diab said. "Developing these strong collaborative initiatives and outreach will benefit all of humanity."

She strongly advocates for effective diversity and inclusion and welcoming everyone equally in the scientific landscape. It is critical to the sustainability of the scientific enterprise.

Diab will be the LTI's second full-time director. The institute's founder and first director, Jaime Carbonell, died in February 2020. Professors Jamie Callan and Carolyn Rosé have served as interim directors.

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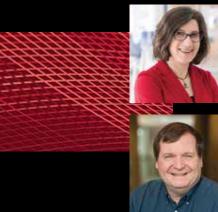
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Names in the News

SCS IN THE NEWS



Faculty member Weina Wang received the 2023 **Rising Star Research Award** from ACM SIGMETRICS for developing tools that deepen understanding of complex, heterogeneous stochastic systems.



Faculty members Lorrie Faith Cranor and Mark Stehlik have been elevated to University Professor, the highest distinction a CMU faculty member can receive.



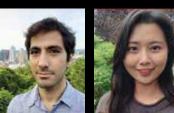
MLD Ph.D. student So Yeon (Tiffany) Min has been named a 2023 Apple Scholar in Artificial Intelligence and Machine Learning.



CSD post-doc Sam Westrick received ACM SIGPLAN's John C. Reynolds Doctoral Dissertation Award for his work on memory disentanglement.

Shantanu Gupta, Ian Waudby-Smith, Emre Yolcu and Minji Yoon — all Ph.D. students with ties to SCS — have been named 2023 Amazon Graduate Research Fellows.







HCII faculty member Chris Harrison earned the UIST Lasting Impact Award for his 2011 work on OmniTouch, a wearable system that turns everyday surfaces into an interactive screen.



SCS Professor Eric Xing received a 2022 Amazon **Research Award**, which supports research at academic institutions and nonprofits in areas that align with the organization's mission to advance customerobsessed science.

Katerina Fragkiadaki, an assistant professor in MLD, earned the inaugural **SCS** JPMorgan Chase Career Development Professorship.

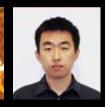
















Eight SCS faculty members received NSF CAREER Awards totaling more than \$4.5 million (Top L-R): Andrej Risteski, Wenting Zheng, Jun-Yan Zhu, Matthew O'Toole, Sauvik Das, Zhihao Jia, Dimitrios Skarlatos and Hirokazu Shirado.

HCII researchers John Stamper, Norman Bier and Steven Moore are part of a team that won first place in the XPRIZE Digital Learning Challenge.



THE LINK

Alan Guisewite Was a Robotics Institute Factotum

MATT WEIN



lan Guisewite, an operations assistant in the Robotics Institute for 40 years, died earlier this year. He was 74.

His official title was operations assistant. But between his technical capabilities, institutional memory

and seemingly comprehensive knowledge of building materials, Alan Guisewite was a veritable Swiss Army knife in the Robotics Institute for 40 years.

Guisewite, who spent his entire 50-year career at Carnegie Mellon, died on Sunday, March 12. He was 74.

"You couldn't write a job description for what Alan did," said Mel Siegel, an emeritus professor in RI who worked with Guisewite for more than 20 years. "He was a factotum for the Robotics Institute. You couldn't just go out looking to find someone like him. The breadth of his knowledge was incredible."

Born in Utica, New York, in 1948, Guisewite grew up in the Pittsburgh suburbs of Verona and Penn Hills. He graduated from Penn Hills High School in 1966, and earned an associate's degree in electrical engineering from the Community College of Allegheny County's Boyce Campus in 1972.

In 1973 he started working as an electronics technician in CMU's Biomedical Engineering Program, a precursor to today's Department of Biomedical Engineering. There, he helped design and fabricate everything from a device that measured the physical movement of a beating heart to early LED-based pulse oximeters. "Alan was such a unique character. Very intelligent, but simple and unassuming."

— JEAN HARPLEY

In 1983, when Siegel needed help in his growing Intelligent Sensor, Measurement and Control Lab, he hired Guisewite away from the Department of Electrical and Computer Engineering.

"We were doing process improvement. Someone would come to us and say, 'Hey, can you make this work better for us?" Guisewite said in an interview earlier this year. "We weren't just working on a project and spinning it off. We were jumping from project to project, and that made it a lot of fun."

During his years in Siegel's lab, Guisewite helped build everything from an LED-based navigation system and a computerized nanobrewery to mobile robots for conducting aircraft safety inspections and machines capable of measuring the thickness of individual strands of fiberglass.

"Twice a week, he got at least two post office bags full of catalogs and magazines — catalogs from optics companies, electronic component companies, scientific instrument manufacturers," Siegel said. "He read all of it. He kept all sorts of materials, different kinds of Styrofoam, polyethylene bottles in every size you could imagine. He just had it all and he knew where everything was."

As Siegel wound down his research in the early 2000s, Guisewite's talent for building things remained in high demand around the Robotics Institute. He helped build Ralph Hollis' Microdynamic Systems Lab, worked for Cameron Riviere's Medical Instrumentation Lab and assisted Lee Weiss on multiple projects.

He also worked on numerous projects with Gregg Podnar, including a low-cost, first-response disposable robot; early versions of the ChargeCar; and a fleet of Robot Sensor Boats — autonomous kayaks they piloted in Oakland's Panther Hollow Lake.

But it was the breadth of his knowledge that most impressed his colleagues.

"Alan was such a unique character. Very intelligent, but simple and unassuming," said Jean Harpley, an academic program manager in RI and a friend of Guisewite. "He didn't flaunt his knowledge, but if you were interested, he'd engage and share mind-numbing facts that made you wonder, "Who knows this stuff?' Alan did, and he took great joy in sharing it."

"In about 1992, I broke my wrist playing soccer," Siegel said. "I described what had happened to Alan and he said, 'Oh yes, a Colles fracture!' You don't encounter that much. How did he know that?"

A longtime rockhound and mineral collector, Guisewite amassed a collection of roughly 10,000 mineral specimens from around the world over the course of his life, all of which he arranged to donate to the Carnegie Museum of Natural History. His collection constitutes the largest single donation of its kind in the museum's history.

In honor of Guisewite and his 50 years of service to the university, CMU created the Alan Guisewite Fellowship, which will financially assist graduate students in the Robotics Institute. Guisewite hopes it will keep students interested and involved.

"There's a lot going on here," he said. "There's a lot you can do, whether it's on your own or with another student or professor or staff. You can get involved."

SCS MOURNS LOSS OF COMPUTER VISIONARY, ENTREPRENEUR

Edward Fredkin

MATT WEIN



dward Fredkin, one of the most influential computer science theorists and thinkers of his generation who spent part of his career at CMU, died June 13, 2023. He was 88. Fifty years ago, few people, if any, could possibly have foreseen the way artificial intelligence would grip our imaginations and consume the public discourse. But if anyone did, it was probably Edward Fredkin. Fredkin, who spent part of his career as a

distinguished career professor at CMU, died June 13 in Brookline, Massachusetts. He was 88.

"Ed could have more ideas in a day than many of us could in a month," said Raj Reddy, the Moza Bint Nasser University Professor of Computer Science and Robotics in CMU's School of Computer Science, who knew and worked with Fredkin since the mid-1970s. "Some of them were harebrained ideas, but there were a lot of very good ones."

Numerous innovations and theories bear his name, from the Fredkin Gate to Fredkin's Paradox — his ideas on digital philosophy. Fredkin conceived of everything as nothing more than bits of information, and the universe as one all-encompassing computer. Information, he said, was more fundamental than matter and energy. "Ed could have more ideas in a day than many of us could in a month." — RAI REDDY

Fredkin was born Oct. 2, 1934, in Los Angles to Russian immigrant parents. Though he spent much of his career in and around computing, Fredkin's initial interests included chemistry and physics. After graduating from high school in Los Angeles, he enrolled in the California Institute of Technology, but dropped out during his sophomore year to enlist in the Air Force. He trained as a fighter pilot, but the military found his technical skills impossible to ignore and detailed him to the Lincoln Laboratory, a Pentagon-funded innovation hub at the Massachusetts Institute of Technology.

Upon exiting the service, Fredkin spent several years on the industry side of the still-nascent computing field. He founded Information International Inc., which produced high-precision digital-to-film scanners. It also made him one of tech's first and most successful entrepreneurs.

In 1968, Fredkin joined the faculty at MIT as a full professor, an unheard-of leap in academia for someone without a bachelor's degree. During his tenure there, he headed Project MAC, a research initiative that made advances in multiple access computers, operating systems and an AI precursor known as machine-aided cognition.

In 1979, Reddy invited Fredkin to speak at a conference he was chairing in Japan.

"In AI, there are all these problems that we call grand challenges, and I suggested to Ed that it would be good to set up some prizes for these," Reddy said. "He agreed, and we set up the Fredkin Prize in 1980."

Using money Fredkin donated to CMU, the Fredkin Prize promised \$100,000 to the designers of the first computer capable of defeating a world chess champion. In 1984, Fredkin left MIT and joined the CMU faculty as a distinguished career professor. That year, the university awarded him the Dickson Prize for Science.

In 1997, an IBM-built chess computer called Deep Blue defeated Garry Kasparov, the reigning world chess champion, and took home the Fredkin Prize. Later that year, Fredkin and CMU used the money left over from the challenges to endow two chairs in SCS. Tom Mitchell and Red Whittaker received the first two Fredkin professorships.

"Beyond all that Ed was and did in the world and for CMU, he was wonderful to and for me in so many ways," Whittaker said. "For he and Raj to endow a chair for me was such a validation and empowerment at a time when robotics didn't have many chairs."

In addition to his time at CMU and MIT, Fredkin taught physics at Boston University. He also never lost his love for flying and became an accomplished hobbyist pilot.

"During the DARPA Grand Challenge, no one was allowed on the course and even communicating status was disallowed," Whittaker said. "Ed pointed out that DARPA hadn't controlled airspace over the course, so he wanted to fly low and slow overhead to convey real-time status to me about how we and the competitors were doing. Who does that?"

Fredkin is survived by his wife, Joycelin; sons Richard and Michael; daughters Sally and Susan; six grandchildren and one great-grandchild.

COMPUTING PIONEER LEAVES LASTING MARK ON TEACHING, RESEARCH

William Wulf

SUSIE CRIBBS

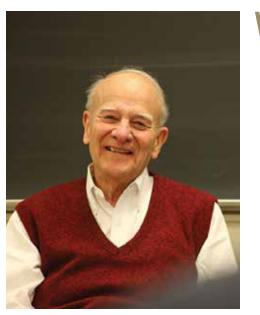


Image Courtesy of the University of Virginia

illiam Allan (Bill) Wulf earned one of the first doctorates in computer science; developed crucial advances in programming languages and compilers; and helped shape the future of computer science education, research and national policy. A pioneer in nearly all aspects of the field, the former

Carnegie Mellon University faculty member and honorary degree recipient died on Friday, March 10, 2023. He was 83. Wulf joined the CMU faculty as an assistant

professor of computer science in 1968 after earning the first Ph.D. from the University of Virginia's newly founded Department of Applied Mathematics and Computer Science. He rose to full professor in 1975. While at CMU, Wulf helped develop C.mmp, a multiprocessor system for which he and his students designed the software, known as Hydra. Hydra was written in BLISS, or Bill's Language for Implementing System Software, a programming language later adopted by Digital Equipment Company. He also helped develop one of the first programming languages that incorporated abstract data types and formal verification, known as Alphard (the brightest star in the Hydra constellation). His work gave CMU the strong foundation in software engineering that continues to this day.

"Bill often said, 'It is better to build bridges than walls,' and he lived his life accordingly."

"Bill was a creative and thoughtful leader. He was one of the early systems faculty in computer science at CMU and helped set us on the path to prominence in software engineering," said Mary Shaw, one of Wulf's Ph.D. advisees and the Alan J. Perlis University Professor of Computer Science at CMU. "He brought a true engineering sensibility to operating system and programming language design."

While on campus, Wulf met his partner in both life and work, Anita Jones, who earned her Ph.D. in computer science and served on the faculty until she and Wulf left the university to found Tartan Laboratories. The software company, based on Wulf's research, specialized in compilers for programming languages, particularly Ada, and was one of the first companies that would transform Pittsburgh from steel town to tech hub. Wulf was also a founder of the city's High Technology Council, known now as the Pittsburgh Technology Council.

Texas Instruments acquired Tartan Laboratories in 1988, and Wulf returned to UVA, where he would go on to have an illustrious career as both a researcher and educator. He also served as assistant director of the National Science Foundation Computer and Information Science and Engineering directorate and director of the National Academy of Engineering.

"The Carnegie Mellon community mourns the loss of Bill Wulf, and we extend our deepest condolences to his wife, Anita, and their family," CMU President Farnam Jahanian said. "Bill's brilliant scholarship, research and thought leadership have left a profound impact on our nation's science and innovation enterprise and on the institutions he served, including the National Science Foundation, the National Academy of Engineering and CMU. Our university was incredibly fortunate to have counted Bill as a Tartan, especially in our School of Computer Science, where his legacy of innovation and commitment to creating opportunities for others will continue to reverberate."

Wulf earned countless honors throughout his career and held membership in nearly every major professional society in his field. He also helped establish the Virginia Academy of Science, Engineering and Medicine, and was a founding trustee of Egypt's New Library of Alexandria. He received five honorary degrees, including the one from CMU in 1999; authored more than 100 papers and three books; held two U.S. patents; and supervised more than 25 Ph.D. students in computer science.

"The loss is personal as well as professional to me. Bill was my thesis advisor, along with Alan Perlis," Shaw said. "His research style and values had a large impact on mine, in particular starting me on the path of questioning conventional wisdom — a strategy that has served me well. He was a mentor, a collaborator and a friend."

According to UVA, Wulf's talent and devotion to uniting people for a purpose — for better engineering, better policy and a better society was his greatest contribution.

"Bill often said, 'It is better to build bridges than walls,' and he lived his life accordingly," said UVA Professor Emeritus Gabriel Robins.

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