Profile of Christos Papadimitriou

Farooq Ahmed
Science Writer

When Christos Papadimitriou graduated in 1972 from the National Technical University of Athens in his native Greece, he arrived at a breaking point. Like all Greek men he was required to join the armed forces, and he enlisted while the country struggled under military rule.

"I went in fully expecting to serve and then work quietly as an engineer somewhere," Papadimitriou recalls. "But during military service, the ruthlessness of the regime struck me in a very powerful way. I knew that I could not stay." He applied to graduate school and joined Princeton University's fledgling computer science group. Democratic reforms in 1974 ousted Greece's military junta the same year that Papadimitriou earned a Master's degree. He would complete his doctorate two years later in electrical engineering and computer science.

In the past four decades, Papadimitriou's influence on the field of computer science has been far-reaching. His articles launched new research areas, his textbooks have become standards, and his works of fiction—two novels and a graphic novel—have introduced the history of logic and computer science to broad audiences. In 1996 Papadimitriou joined the University of California, Berkeley, where he holds the C. Lester Hogan Chair of Electrical Engineering and Computer Science. He was elected to the National Academy of Sciences in 2009.

Leaving Athens

Born to educators in a small town outside of Delphi in the Greek mountains, Papadimitriou moved to Athens with his family when he was five years old. The "mountain accent" he carried into the financial and political capital of Greece earned him few friends. "That grief led me to studying as a way of escaping my social problems."

At the National Technical University of Athens, Papadimitriou studied mechanical and electrical engineering. However, he wasn't keen on the subject. Instead, Papadimitriou stole into the university's computer laboratory and taught himself how to program. "There was an IBM 1620 computer, probably a million times less powerful than today's cellphones. It was closely guarded but that was the only thing that really got my attention."

Complexity

After graduating from college and serving in the military, Papadimitriou left Greece for northern New Jersey. When he arrived at Princeton in 1973, the computer science group at the university had five people. However, for Papadimitriou the setting provided a stimulating intellectual environment and an opportunity to influence an emerging field.

"For the first time in my life," he admits, "I found something that I really enjoyed—and I was good at it! Suddenly, I decided to take my graduate studies very seriously." Papadimitriou worked with Kenneth Steiglitz and began his lifelong investigations into computational complexity.

"It all started with Alan Turing," Papadimitriou says. In 1936 Turing, a British logician who established the conceptual framework for computer science, proved that some problems could not be solved by computers: that no algorithm could be written to find solutions, even if the questions were well-defined (1). "Computer science was a field born with a dire understanding of its limitations," adds Papadimitriou.

Building on Turing's and others' work, in 1971 the University of Toronto's Stephen Cook devised a way to distinguish between problems that could be solved quickly, in polynomial time, and others for which the time to uncover a solution increased exponentially (2). In the field's parlance, the latter class of problems is now referred to as "NP-complete" or "NP-hard."

Papadimitriou describes the difference between these types of problems as similar to trying to find a needle in a haystack. "If the needle's ferromagnetic then you can use a magnet, and you're done. But what if that needle is plastic? You have to look under every blade of hay."

"I decided to dedicate my career to try and understand the difference between the needles," Papadimitriou says. "That's complexity theory." Papadimitriou proved that the historic traveling salesman problem, in which one has to calculate the shortest route between several cities such that each city is only visited once, is of the NP-complete (3) type. His work on complexity, often with collaborator Mihalis Yannakakis, now at Columbia University, transformed and expanded the subject (4).

Christos Papadimitriou. Image courtesy of Eirene-Chloe Markenscoff Papadimitriou.

Academic Freedom

When he received his doctorate from Princeton, computer science was still a small enough field that Papadimitriou felt like he "knew all that there was to know at the time." He left as a theoretician with a determination to advance the field and ensure that it became one that would solve "significant and meaningful" problems.

Over the next two decades, Papadimitriou taught at six different institutions: Harvard University, Massachusetts Institute of Technology, Stanford University, the National Technical University of Athens, the University of California at San Diego, and the University of California at Berkeley. Papadimitriou's return in 1981 to Athens, where he taught for at least one semester for the next seven years, provided, he says, a vindication. "It was a bold, perhaps risky

This is a Profile of a recently elected member of the National Academy of Sciences to accompany the member's Inaugural Article on page 15881.

www.pnas.org/cgi/doi/10.1073/pnas.1405579111

decision for me to return. But I was excited to contribute to the development of computer science in Greece."

It was at Berkeley's northern California campus, however, that Papadimitriou found an intellectual home. "There is a very aggressive form of academic freedom at Berkeley. I first visited as a Miller Fellow in 1978, and it gave me a feeling of extreme freedom: If it feels good intellectually, then you must do it! And do it with passion."

From the mid-1970s to the mid-1990s, as computer science matured, Papadimitriou taught nearly every course, from programming languages to compilers, operating systems, and databases. His 1982 textbook, *Elements of the Theory of Computation* (5), written with Harvard University's Harry Lewis, explained the foundations of emerging fields and influenced how courses on the subject were taught. With his graduate adviser Steiglitz, Papadimitriou published a graduate textbook on algorithms and complexity called *Combinatorial Optimization* in 1982 (6). A more recent textbook on algorithms has become a standard for undergraduates (7).

"Frankly," Papadimitriou explains, "teaching is the only way I know to understand something. But these days," he adds with a laugh, "the courses have become so complicated that I doubt I could pass them!"

In his research, Papadimitriou used mathematical tools to uncover complexity, wherever it exists. He defined new classes of complexity, which have led to breakthroughs and new ways of understanding computational problems (8, 9). Extending his work beyond computer science, Papadimitriou and colleagues found that a two-dimensional protein-folding model, the hydrophobic-polar model, was of the NP-complete type (10). Papadimitriou's work on databases in the 1970s and 1980s culminated in a 1986 monograph, *The Theory of Database Concurrency Control* (11).

The World Wide Web

After returning to the University of California, Berkeley in January 1996, Papadimitriou reached another inflection point in his career. In the early 1990s, the Internet and the World Wide Web had reached a critical moment. A plethora of small voices were virtually publishing content, and major companies were profiting without a brick-and-mortar presence.

"The Internet," explains Papadimitriou, "was something completely new and different. Like mathematics, its existence is based on minimalistic principles, but you cannot point to a designer, a committee, a user, or a company that made it happen. It grew out of the interaction of many."

This line of reasoning led to a realization: "Computer science was no longer about the computer. The creation of the Internet was transforming computer science into a natural science. But it was also transforming computer science into a social science! Because you cannot understand the Internet without understanding the incentives of the entities that use and continue to create it."

Papadimitriou focused on understanding the Internet as a neuroscientist approaches the brain or an astrophysicist views the universe. For his contributions, in 2002 Papadimitriou received the Donald E. Knuth Prize, awarded jointly by the Association for Computing Machinery and the Institute of Electrical and Electronics Engineers.

Christos as featured in LogiComix. Image courtesy of Apostolos Doxiadis, Christos Papadimitriou, Alecos Papadatos, and Annie di Donna, 2009, Logicomix Print Ltd. and Bloomsbury Publishing Plc.

Anarchy

Papadimitriou's work has helped create and engage new scientific disciplines. Investigations into decision making and mathematical models of conflict resolution drove contributions to algorithmic game theory, a field at the intersection of economics and computer science.

In 1999 Papadimitriou and Elias Koutsoupias, now at the University of Oxford, defined the price of anarchy, a mathematical way of measuring how performance in a system degrades as a result of the selfishness of its users (12). "Imagine," Papadimitriou explains, "that the Internet was not run by thousands of providers but instead by one benevolent dictator who wanted to maximize social welfare. How much better would it be than what we have today? That's what we call the price of anarchy." Often, the answer is, "Not that much."

His recent work in game theory concerns the Nash equilibrium, a fundamental concept in economics for which Princeton's John Nash, won a Nobel Prize in 1994. The Nash equilibrium describes the situation in which

Papadimitriou and his team discuss how to tell the story of British mathematician Betrand Russell's epic search for the truth. Image courtesy of Apostolis Doxiadis, Alecos Papadatos, Annie di Donna, and Anne Bardy, 2009, Logicomix Print Ltd. and Bloomsbury Publishing Plc.

agents in a market or at a game who know the behavior of their competitors do not change their own strategies because doing so would not be gainful. As a result, the agents reach an unchangeable balance. Papadimitriou and colleagues determined that finding the Nash equilibrium in a game is an intractable problem (13). For his research on algorithmic game theory, in 2012 Papadimitriou received the Gödel Prize for theoretical computer science, and he shared with his coauthors, Paul Goldberg and Constantinos Daskalakis, the Game Theory Society's prize in Game Theory and Computer Science.

Algorithmic Sex

In addition to teaching at Berkeley, Papadimitriou holds a senior scientist position at the university's Simons Institute for the Theory of Computing, a post that has allowed him to further leverage his understanding of computation. By studying algorithms that simulated biological reproduction, he and others explained a persistent mystery in evolutionary biology: Why is sexual reproduction so prevalent in nature when asexual reproduction seems far more efficient at promoting fitness (14, 15)?

Papadimitriou explains that "sex does a better job at increasing mixability, which is the ability of different genes to perform in varied genetic environments. This gives organisms better long-term chances." He adds that "there are many more mysteries remaining in evolution, and I have a feeling that computation and complexity may hold the key." Papadimitriou's Inaugural Article highlights the utility of computation in areas beyond computer science and deploys computation as a metaphor to reveal approaches to challenging problems in science (16).

Stories

In the last decade and a half, in parallel with his teaching and research, Papadimitriou has embraced the humanities. He published two novels: *Turing (A Novel about Computation)* (17), a love story that features a virtual Alan Turing as a character, and *Independence* (18), a family drama that tackles the history of modern Greece. With author Apostolos Doxiadis, Papadimitriou wrote the internationally best-selling graphic novel *Logicomix* (19), dramatizing Bertrand Russell's quest to codify the logical foundations of mathematics.

Papadimitriou views his novelistic works as an extension of his science. "I started writing quite suddenly, and it made me very aware of how important stories are in science, in my science. I've found that I can almost never understand a concept unless I reach it through a story."

1 Turing AM (1937) [Delivered to the Society November 1936]. On computable numbers, with an application to the Entscheidungs problem" *P Lond Math Soc* Series 2,42:230–265.
2 Cook SA (1971) The complexity of theorem-proving procedures. *Proceedings of the 3rd Annual ACM Symposium on Theory of Computing* (ACM, New York), pp 151–158.
3 Papadimitriou CH (1977) The Euclidean travelling salesman problem is NP-complete. *Theor Comput Sci* 4(3):237–244.
4 Papadimitriou CH, Yannakakis M (1991) Optimization, approximation, and complexity classes. *J Comput Syst Sci* 43(3):425–440.
5 Lewis HR, Papadimitriou CH (1982) *Elements of the Theory of Computation* (Prentice-Hall, Englewood Cliffs, NJ).
6 Papadimitriou CH, Steiglitz K (1982) *Combinatorial Optimization* (Prentice-Hall, Englewood Cliffs, NJ).
7 Dasgupta S, Papadimitriou CH, Vazirani U (2006) *Algorithms* (McGraw-Hill, New York).
8 Johnson DS, Papadimitriou CH, Yannakakis M (1988) How easy is local search? *J Comput Syst Sci* 37(1):79–100.
9 Papadimitriou CH (1994) On the complexity of the parity argument and other inefficient proofs of existence. *J Comput Syst Sci* 48(3):498–532.
10 Crescenzi P, Goldman D, Papadimitriou C, Piccolboni A, Yannakakis M (1998) On the complexity of protein folding. *J Comput Biol* 5(3):423–465.
11 Papadimitriou CH (1986) *The Theory of Database Concurrency Control* (Computer Science Press, New York, NY).
12 Koutsoupias E, Papadimitriou CH (2009) Worst-case equilibria. *Comput Sci Rev* 3(2):65–69.
13 Daskalakis C, Goldberg P, Papadimitriou CH (2006) The complexity of computing a Nash equilibrium. *Proceedings of the Thirty-Eighth Annual ACM Symposium on the Theory of Computing* (ACM, New York), 71–78.
14 Livnat A, Papadimitriou C, Dushoff J, Feldman MW (2008) A mixability theory for the role of sex in evolution. *Proc Natl Acad Sci USA* 105(50):19803–19808.
15 Livnat A, Papadimitriou C, Pippenger N, Feldman MW (2010) Sex, mixability, and modularity. *Proc Natl Acad Sci USA* 107(4):1452–1457.
16 Papadimitriou C (2014) Algorithms, complexity, and the sciences. *Proc Natl Acad Sci USA* 111:15881–15887.
17 Papadimitriou CH (2003) *Turing (A Novel about Computation)* (The MIT Press, Cambridge, MA).
18 Papadimitriou CH (2012) *Independence* (Patakis Publishers, Athens).
19 Doxiadis A, Papadimitriou CH (2009) *Logicomix: An Epic Search for Truth* (Bloomsbury, New York).