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The 2011 Benjamin Franklin Medal in computer and cognitive science presented to John R. Anderson

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Abstract

John R. Anderson is an international leader in the computational representation and simulation of human cognition. He is credited as having developed the first “cognitive architecture”—a computational framework for specifying both the abilities and limitations of human behavior. Anderson has also made fundamental contributions in applying cognitive architectures to practical problems, most notably in the development of intelligent tutoring systems: computer-based tutors that continually infer the cognitive state of the student, striving to determine what the student knows and does not know, and targeting further instruction accordingly. For these achievements, Anderson was awarded the 2011 Benjamin Franklin Medal in Computer and Cognitive Science.

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1. Introduction

Since the earliest days of computing, scientists have worked to endow computers with intelligence—with the ability to think, reason, and act in ways similar to their human creators. Initial research into “artificial intelligence,” as it became known, shed light on both the great promise and the great challenges of such an effort. As this area of research evolved, some scientists became more centrally focused on applying these new ideas to engineering-oriented problems, such as defeating a world-champion chess player. Other scientists, meanwhile, began to focus on using computers to simulate human cognition in order to better understand the fundamental workings of the human mind.

At the same time, the field of psychology was also rapidly evolving, with detailed studies of specific important aspects of human cognition: list memory, mental rotation, visual

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search, and so on. Although this work helped to understand each component of cognition in its own right, very little attention was paid to the interaction among all these components. Allen Newell (winner of the Franklin Institute's Levy Medal in 1992), in a paper aptly titled "You Can't Play 20 Questions With Nature And Win" [1], expressed concern about this state of affairs and wondered how the scientific community could better work toward more integrative theories. His vision of unified theories of cognition, much like grand unified theories in physics, sought to account for the vast scope of human cognition with a minimal set of core principles and processes.

Newell's words still serve as a guiding vision for the field of cognitive science, and no one has contributed more toward achieving this vision than John R. Anderson. He is credited as having developed the first "cognitive architecture"—a computational framework for specifying both the abilities and limitations of human behavior. Anderson's ACT theory specifies, for example, how memorized facts decay over time, how verbal instructions are translated into procedural actions, and how such procedures become more efficient with practice. The specification of human cognition in a cognitive architecture allows for a more rigorous analysis of the most detailed aspects of cognitive processes, as well as the effects of the interaction of the component processes (cognitive, perceptual, and motor) in the context of complex real-world tasks.

Anderson has also made fundamental contributions in applying cognitive architectures to practical problems, most notably in the development of intelligent tutoring systems. Intelligent tutoring systems are computer-based tutors that continually infer the cognitive state of the student, striving to determine what the students knows and does not know, and targeting further instruction accordingly. Anderson and his colleagues incorporated the ACT theory into such a system, and in subsequent studies of the system in local and then national school districts, showed that intelligent tutors can significantly improve student learning. An industry partner further developed Anderson's tutoring systems, and his work in this area is now the core technology for computer-based tutors currently used by over 500,000 students across the United States.

2. History and contributions

As a graduate student at Stanford University, Anderson and his advisor, Gordon Bower, developed a detailed theory of memory along with initial computer simulations of the theory, culminating in their joint book *Human Associative Memory* (1973) [2]. This theory was further developed in Anderson's subsequent book, *Language, Memory, and Thought* (1976) [3], which also began to expand the scope of the theory beyond memory to the complex domain of language and to more general cognitive processes. The latter book also represented a landmark for the field, providing the first description of the ACT (Adaptive Control of Thought) theory that Anderson would continue to develop throughout his career.

ACT, as Newell himself noted [4], was the first unified theory of cognition and the first cognitive architecture: a computational framework intended to embody all the abilities and limitations of the human system, as described in Anderson's seminal work "*The Architecture of Cognition*" (1983) [5]. ACT posited that human cognition could be best represented in terms of two major components: declarative knowledge that encoded basic factual knowledge in addition to the current context, and procedural knowledge that encoded procedural skills as condition-action rules (production rules). The computational

foundation of the ACT theory forced theoretical ideas to be expressed in formal ways, thus lending a greater level of psychological plausibility. In addition, the computational models developed with such a cognitive architecture could be run as computer simulations, generating behavior and making predictions that would be extremely difficult or impossible to generate with simpler, closed-form representations.

The ACT theory evolved a great deal in over three decades of development since its introduction. One important step in its evolution came from a focus on skill acquisition [6], the process by which people learn and adapt procedural skills for new tasks. This work defined skill acquisition in the context of the ACT framework by specifying computational methods for adapting the procedural rules of the behavioral models. In collaboration with Kevin Singley, Anderson also explored how procedural skills may transfer from one task domain to another [7]. These and other aspects of the skill-acquisition work became critical theoretical building blocks in the development of the ACT-based intelligent tutoring systems.

Another extension of the theory was derived from a new approach that Anderson called rational analysis [8]. Rational analysis stated that, in order to filter through the often-vast space of potential theories, one could focus on the task and task context as a window into human problem-solving strategies and behaviors. The upshot of rational analysis was a new formulation of the ACT theory known as ACT-R, the current incarnation of the theory used by an international community of hundreds of researchers as a testbed for understanding and simulating cognitive processes. In fact, one of the most important benefits of ACT (and other cognitive architectures) is that they facilitate community theory-building: when researchers for a certain domain improve the architecture's account of that domain, all users of the architecture immediately benefit from the improved predictions of the new theory.

A third major advance for the ACT theory arose at least in part because of this emphasis on community theory-building. Borrowing ideas from another cognitive architecture (EPIC), ACT incorporated much-improved perceptual and motor processes, allowing the computational simulations to interact with task environments in a much more realistic way. As a result, Anderson and the broader community greatly expanded the scope of the ACT theory in applying it to a wide variety of task domains, ranging from basic experimental tasks (list memory, analogy, decision-making, etc.) to complex real-world tasks (backgammon, driving, air-traffic control, etc.).

A fourth advance, spearheaded by Anderson over the past decade, involved grounding the components of the ACT cognitive architecture in terms of their neural bases. Computational simulations of the theory make predictions about which components—vision, audition, memory, and so on—are active at various temporal points of a task execution. In his most recent book, *How Can the Human Mind Occur in the Physical Universe?* (2007) [9], Anderson demonstrated how ACT's computational mechanisms correspond closely both spatially and temporally to brain-imaging (fMRI) patterns observed in humans performing the same tasks.

Beyond these major theoretical advances, Anderson's work has had an enormous impact in practical terms, most notably in the field of intelligent tutoring systems. Intelligent tutoring systems are computer-based tutors that aim to infer a student's knowledge during all stages of the learning process. Anderson et al. [10,11] pioneered the use of cognitive architectures to perform this inference: by embedding the ACT computational mechanisms within the tutoring system, the system can match the observable behavior of the student with the predicted behavior of the ACT models for that task. The system thus maintains a

continual estimate of the student's knowledge of specific component skills, and then targets instruction to address any deficiencies in this knowledge.

Moving well beyond the controlled laboratory setting, Anderson, along with his students and collaborators, tested their tutoring systems in real classrooms—teaching geometry, algebra, and word-problem solving to high-school students, and teaching computer programming to college undergraduates. These efforts had to confront some of the most critical challenges in education today, some of which—like class attendance—were largely peripheral to the technological task at hand. Nonetheless, the studies demonstrated that computer tutors could, in general, significantly improve learning and raise test scores to approximately one standard deviation above scores obtained via normal classroom instruction. Their work on intelligent tutoring systems later spurred the creation of a company, Carnegie Learning, Inc., to further develop the integrated curriculum, and to this day, the ACT theory remains the core technology for these tutoring systems now used by over 500,000 students across the United States.

From both a theoretical and practical standpoint, Anderson's body of research has had an enormous impact. He has also authored a textbook about cognitive psychology [12] that remains popular, and has advised (to date) 29 Ph.D. students and mentored countless others in building a strong community of computational cognitive scientists. Anderson is very much deserving of the 2011 Benjamin Franklin Medal in Computer and Cognitive Science for his development of the first unified theory of cognition instantiated as a computational cognitive architecture, and its application to intelligent tutoring systems.

3. Laureate's biography

John R. Anderson was born in Vancouver, British Columbia, in 1947. He attended the University of British Columbia and, upon his graduation in 1968, won the Governor-General's Gold Medal as the top student in Arts and Sciences. Anderson attended graduate school at Stanford University to work with Gordon H. Bower (winner of the National Medal of Science in 2005). After working for short periods at Yale University and the University of Michigan, Anderson moved to Carnegie Mellon University in 1978 with his wife, distinguished psychologist Lynne M. Reder, and has worked there ever since. Anderson has received a number of previous honors including the Distinguished Scientific Career Award from the American Psychological Association (1994), election to the National Academy of Sciences (1999), the David E. Rumelhart Prize from the Cognitive Science Society (2004), the Howard Crosby Warren Medal from the Society of Experimental Psychology (2005), and the inaugural Dr. A.H. Heineken Prize for Cognitive Science from the Royal Netherlands Academy of Arts and Sciences (2006).

4. Medal legacy

Previous laureates who, like John Anderson, have made important contributions to the development of computational models of human cognition include:

- 1890 Herman Hollerith (Cresson)
Electric Tabulating Device
- 1904 C.W. Draper (Longstreth)
Development of a computing machine

- 1991 George Miller (Levy)
For being a key developer of cognitive psychology
- 1992 Allen Newell (Levy)
For development of languages and architecture to make computers intelligent
- 1999 Douglas Engelbart (Benjamin Franklin in Computer and Cognitive Science)
For his outstanding contributions in computer hardware and software that revolutionized human–computer interactions
- 1999 Noam Chomsky (Benjamin Franklin in Computer and Cognitive Science)
For his contributions to the world of linguistics and their effects on computer science, and insight into human thought processes
- 2001 Marvin Minsky (Benjamin Franklin in Computer and Cognitive Science)
For development of conceptual model of the mind; artificial intelligence
- 2003 John McCarthy (Benjamin Franklin in Computer and Cognitive Science)
For his multiple contributions to the foundations of artificial intelligence and computer science including the development of the LISP language, the invention of time-sharing interactive programming, and key developments in the application of formal logic to common sense reasoning
- 2006 Donald Norman (Benjamin Franklin in Computer and Cognitive Science)
For the development of the field of user-centered design, which utilizes our understanding of how people think to develop technologies designed to be easily usable
- 2007 Stuart Card (Bower Award and Prize for Achievement in Science)
For fundamental contributions to the fields of human-computer interaction and information visualization.

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