National Medals of Science

On November 13, 1990, President Bush presented the National Medal of Science to twenty renowned scientists, engineers, and mathematicians. The Medal, the highest national award in science, is conferred by the President in recognition of outstanding contributions to knowledge in the physical, biological, social, behavioral, mathematical, or engineering sciences.

Among the recipients of the National Medal of Science were four members of the mathematical sciences community: GEORGE F. CARRIER of Harvard University, STEPHEN C. KLEENE of the University of Wisconsin at Madison, JOHN MCCARTHY of Stanford University, and PATRICK SUPPES of Stanford University.

The National Medal of Science was established in 1959. The recipients are selected from nominations made by the National Academy of Sciences and other scientific and engineering organizations. The selection criteria include the total impact and importance of an individual's work on the present state of science. In addition, achievements of an unusually significant nature are considered and judged in relation to the potential effects of such achievements on the development of scientific thought.

George F. Carrier

George F. Carrier

George F. Carrier was awarded the National Medal of Science for his achievement and leadership in the mathematical modeling of significant problems of engineering science and geophysics, and their solution by the application of innovative and powerful analytical techniques.

Commentary on Carrier's Research

The Managing Editor of *Notices* asked Ivar Stakgold of the University of Delaware to comment on Professor Carrier's research. He responded:

George Carrier is closely identified with the remarkable development of American Applied Mathematics following the Second World War. Through his own research and that of his many students, he has influenced both the direction and style of contemporary applied mathematics. His work is characterized by an interplay of physical and mathematical insights: the uncanny ability to model the essential features of intricate real-world problems and the mathematical power to carry out the analysis to obtain meaningful results.

In engineering science, Carrier has been active throughout his career in the solution of significant technological problems. His very early papers on the mechanics of the rolling of plastic materials had an immediate industrial impact that led to extraordinary manufacturing savings. He has made seminal contributions to the technologies of viscometry, gyroscopy, and centrifugal isotope separation. Again, early in his career, he initiated an enduring involvement in naval matters by his pioneering studies of the effect of underwater explosions on submarine shells. He was also an important contributor to the engineering of space-vehicles, dealing especially with problems of atmospheric reentry and the associated supersonic flow of reacting, radiating gases and their interaction with ablating structures. During the last quarter-century Carrier has produced a major series of papers in the field of combustion, particularly relevant to the performance of internal-combustion engines. Here the full flower of Carrier's talents has been brought to bear on penetrating analyses of highly complex systems, involving aerodynamic, chemical, and thermal processes in multiphase mixtures.

Carrier's manifold contributions to geophysics started in 1950 in his paper on wind driven circulation in ocean basins and have continued to this day. He has deduced quantitative results for the mixing of ground and sea water that results from the diffusion of tides into permeable islands (like Hawaii). His oceanographic studies have explained the mechanics of water waves on sloping beaches and in confined harbors, with results directly pertinent to ship handling and deployment. He has analyzed the behavior of ocean currents, in general, and the Gulf Stream in particular. He explained the dynamics and evolution of tsunamis as they are generated by earthquakes, travel across the ocean, and strike islands or continental boundaries. In Carrier's atmospheric research, hurricanes and tornadoes have been of special interest, and his comprehensive studies of the exceptionally intricate energetics and motions of hurricanes as they interact with land and sea are milestones of the field. Most recently, large fires, firestorms, and, on a global scale, nuclear winter, have also received the penetrating, insightful Carrier treatment.

As important as the impact has been of the many specific solutions to scientific and technological problems that Carrier has produced, of equal significance are his contributions to applied mathematics itself. His problem-solving papers provide vivid illustrations of how to invoke similarity, dimensional, and scaling considerations to assess the relative importance of energies, forces, and responses involved in complex phenomena, seeking out those that are essential for basic understanding, and reserving for later elaboration on those that are less central; establishing succinct mathematical models and formulations elegantly tailored to the problems under consideration; exploiting, and often inventing, sophisticated mathematical techniques to extract, with striking finesse, crisp quantitative solutions to the governing differential and integral equations; and, finally, providing perceptive interpretations of the results. Even more explicitly, he has published and lectures widely on applied mathematical methods, promulgating the boundary-layer approach, singular perturbation methods, asymptotics and complex variable techniques, among others. His papers and lectures on methodology, as well as the three textbooks on applied mathematics that he co–authored, have been extremely influential in the training and education of applied mathematicians everywhere.

Carrier has been unstinting in his services to the scientific and technical community, academia, industry, and the nation on very many important official and advisory groups. His extended membership in the Naval Studies Board of the National Research Council (NRC) is sponsored by the NRC. Carrier's personal scientific wisdom and skills, his vast breadth of knowledge, and his high standards, integrity, and leadership came to full play during this study, which resulted in the widely acclaimed NRC report on Nuclear Winter.

The National Medal of Science is a fitting recognition of a truly impressive career.

Biographical Sketch

George Francis Carrier was born in Millinocket, Maine on May 4, 1918. He earned a Mechanical Engineer degree (a bachelor's-level degree) in 1939 and a doctorate in applied mechanics in 1944, both from Cornell University. From 1946 to 1952, he advanced from assistant professor to professor of engineering at Brown University. He then moved to Harvard University as Gordon McKay Professor of Mechanical Engineering. Since 1972, he has been T. Jefferson Coolidge Professor of Applied Mathematics at Harvard.

Professor Carrier has served as a member of the Council of the Engineering College of Cornell University for many years. He was an associate editor of the *Journal of Fluid Mechanics* from 1956 to 1986 and has been an editor of *Quarterly of Applied Mathematics* since 1952. A member-at-large of the AMS Council from 1971 to 1973, he was also on the organizing committee for the Summer Seminar in Modern Modeling of Continuum Phenomena (1975) and the AMS-MAA-SIAM Joint Projects Committee (1977-1978). In addition, he served on the AMS-SIAM Committee on the 1980 Wiener Prize and the Von Karman Prize Committee of SIAM (1970-1971 and 1983-84).

Professor Carrier has presented numerous invited lectures, including those at the Summer Institute on Mathematical Problems in Geophysical Sciences (1970) and the Summer Seminar on Modern Modeling and Continuum Phenomena (1975). In 1969, he was the von Neumann Lecturer for SIAM. He was also a speaker in the symposium "American Mathematics Entering Its Second Century" held at the annual meeting of the American Association for the Advancement of Science in 1988 to celebrate the centennial of the AMS.

Professor Carrier's many awards and honors include the Richards Memorial Award (1963) and the Timoshenko Medal (1978) of the American Society of Mechanical Engineers (ASME), the Von Karman Medal of the American Society of Civil Engineers (1977), the Von Karman Prize of SIAM (1979), the Applied Mathematics and Numerical Analysis Award of the National Academy of Sciences (1980), the Silver Centennial Medal of ASME (1980), the Fluid Dynamics Prize of the American Physical Society (1984), and the Dryden Medal of the American Institute of Aeronautics and Astronautics (1989). A member of the National Academy of Sciences, the National Academy of Engineering, and the American Philosophical Society, he is also a fellow of the American Academy of Arts and Sciences, an honorary member of ASME, and an honorary fellow of the British Institute of Mathematical Applications.

Stephen C. Kleene

Stephen C. Kleene was awarded the National Medal of Science for his leadership in the theory of recursion and effective computability and for developing it into a deep and broad field of mathematical research.

Stephen C. Kleene

Commentary on Kleene's Research

The Managing Editor of *Notices* asked Yiannis N. Moschovakis of the University of California at Los Angeles to comment on Professor Kleene's research. He responded:

Kleene's name is inextricably bound with the theory of **recursion** and **effective computability**, which he founded and helped develop into a central field of mathematical research. Recursion theory today flourishes as an important part of pure mathematics with its own deep problems and concerns, but it has also yielded important applications to many other mathematical areas and to computer science. About the latter, it is hard to see how theoretical computer science could have reached maturity as an intellectual discipline without the foundational underpinning of the notions and results from recursion theory due to Kleene.

For purposes of classification we can divide Kleene's main scientific contributions into four major areas.

(1) **Classical recursion theory.** Between 1933 and 1936 at least three different classes of functions on the integers were defined by Church, Gödel and Turing, each of them claiming to capture a natural aspect of computability. Very quickly these definitions were all proved equivalent by Church, Kleene, Post and Turing, and Church proposed that *this* (common, rigorous) *notion of recursive function coincides with the intuitive notion of computable number-theoretic function. Church's Thesis* (now rarely disputed) has been called "the first natural law of pure mathematics" and made it possible to prove rigorously that specific functions *are not computable* by showing that they are not recursive. In applications to many areas of mathematics, one can show that specific classification problems are *absolutely unsolvable* by showing that the corresponding functions which express them are not formally recursive.

In a sequence of pioneering papers published between 1936 and 1943, Kleene established the basic mathematical properties of the class of recursive functions, proved the key results justifying Church's Thesis and created the fundamental tools which made it practical to establish the undecidability of problems in all areas of mathematics. His most significant contributions at this level were conceptual and included the introduction of *partial recursive functions, relative recursion* and *the arithmetical hierarchy* of relations on the integers; there were technical contributions too, including the (second) *recursion theorem* whose ten line (ingenious) proof and wide applicability suggest that, even in mathematics, sometimes "less is more." Later (with Post), Kleene used relative recursion to define *degrees of unsolvability* and to lay the foundations of their theory, now developed to one of the richest and mathematically most sophisticated research areas of logic.

The new field of **recursive function theory** was "formally established" with the publication in 1952 of *Introduction to metamathematics*, surely one of the most influential mathematical monographs of our time.

(2) **Hyperarithmetic, inductive, and analytical relations.** The arithmetical hierarchy classifies (by their degree of unsolvability) those relations which are definable in the first-order language of arithmetic. In a sequence of path-breaking papers begun in 1955, Kleene extended this classification to the wider classes of hyperarithmetic, inductive, and analytical relations which can be defined (roughly) first by iterating first-order definitions in arithmetic into the "constructive" transfinite, and then by using the language of second-order arithmetic in its full strength. The work here is highly original and technically brilliant and earned for Kleene (in 1983) the Steele Prize of the American Mathematical Society.

One of the main results in this work is the *Suslin-Kleene Theorem* which identifies the hyperarithmetic relations with those definable by second-order prenex formulas with just one function quantifier (of either kind) in their prefix. It was proved solely by Kleene, but was soon understood as an *effective version* of Suslin's fundamental result of descriptive set theory, proved in 1917. The discovery of this connection led to the birth of the field of *effective descriptive set theory*, in which results about recursive functions are applied to classical analysis and to the solution of old problems about definability in the continuum. Among the standard tools of this field are many methods introduced by Kleene, particularly his fundamental method of proof by "effective transfinite recursion."

(3) **Recursion in higher types.** In another sequence of highly original papers begun in 1959 and continuing until very recently, Kleene studied functionals which can

be defined by recursion but take as arguments objects of arbitrary (finite) type over the integers. This work is deep, hard, and not yet completely appreciated by the mathematical community. Its greater impact to date has been on the *general* (abstract) theory of recursion *on arbitrary* (even non-constructive) domains, the objects of finite type over the integers being a typical case. In this connection, Kleene also introduced "countable functionals," another example of "generalized" computability theory, which has had a strong influence in theoretical computer science. Ultimately the ideas of higher type recursion are likely to influence theoretical computer science even more, because of the fundamental role that recursion plays in the specification of algorithms.

(4) **Intuitionism**. As early as 1945 Kleene introduced a (recursive) *realizability interpretation* of intuitionistic number theory which (for example) understands a statement of the form $(\forall x)(\exists y)A(x,y)$ to mean that "some recursive function f produces for each x a $y = f(x)$ which further "realizes" $A(x,y)$—and in particular satisfies $A(x,y)$ if this formula has no more quantifiers. The gist of the idea is that a *constructive assertion* of some statement A can be understood (at least partially) as a *classical assertion* that a recursive function exists which *realizes* some constructive (or computable) aspect of A. Kleene conjectured that every theorem of intuitionistic number theory was realizable in this sense and his student David Nelson verified the conjecture shortly afterwards. Later Kleene introduced a whole slew of distinct realizability interpretations and turned the method into a fundamental tool for the metamathematical study of intuitionistic systems, particularly in the 1965 monograph *The foundations of intuitionistic mathematics, especially in relation to recursive functions* written jointly with his student Richard Vesley. The main subject of the Kleene-Vesley monograph is a formalized axiomatization of Brouwer's celebrated theory of real numbers within the classical language of second order arithmetic. Intuitionistic analysis had been formalized before (by Heyting), but Kleene's choice of a familiar classical language for his axiomatization made it much easier for non-intuitionists to understand Brouwer's ideas. Brouwer's analysis is inconsistent with classical logic, and Kleene gave the first (classically valid) proof of its consistency (with intuitionistic logic), using a realizability interpretation. Still more recently, the theory of realizability has become very important in the study of interpretations of programming languages where the same problem of classical interpretations of constructive assertions crops up.

From among Kleene's papers not directly related to these main strands of his research, we should mention his characterization of *regular events* published in 1956, a result which is technically quite simple but has become extremely useful in the study of *formal languages* and *grammars*, both in computer science and in linguistics.

Biographical Sketch

Stephen Cole Kleene was born January 5, 1909 in Hartford, Connecticut. He received his A.B. from Amherst College in 1930 and his Ph.D. from Princeton University in 1934. He remained at Princeton, first as an instructor and then as an assistant, until 1935, when he moved to the University of Wisconsin. He went to Amherst College during 1941-1942 and then returned to Wisconsin. While at Wisconsin, he served as chair of the department (1957-1958, 1960-1962) and dean of the College of Letters and Science (1969-1974). In 1964, he was appointed to a Cyrus C. MacDuffee Professorship, which he held until 1979, when he assumed his current position as Professor Emeritus of Mathematics and Computer Science and Emeritus Dean of Letters and Science.

Professor Kleene was a member of the Institute for Advanced Study (1939-1940, 1965-1966) and a visiting professor at Princeton University (1956-1957). He held a National Science Foundation grant at the University of Marburg (1958-1959) and was also a Guggenheim Fellow (1949-1950). In 1957-1958, he served as a member of the mathematics division of the National Research Council and, from 1969 to 1972, as the chairman-designate of the division of mathematical sciences. He served as president of the International Union for History and Philosophy of Science in 1961 and as the president of the Union's division of logic, methodology, and the philosophy of science from 1960 to 1962. During 1966-1967, he was acting director of the mathematics research center of the U.S. Army.

Professor Kleene has served on several AMS committees, including the Organizing Committee for the Symposium on Recursive Functions (1961), and the Nominating Committee for the 1966 Election. He presented invited addresses at AMS meetings in Chicago (1954) and in Kenosha, Wisconsin (1980). He also presented a sixty-minute talk at the 1958 International Congress of Mathematicians in Edinburgh.

The honors and awards presented to Professor Kleene include the AMS Steele Prize (1983) and election to the National Academy of Sciences and to the American Academy of Arts and Sciences. He served as vice president (1941-1942, 1947-1949) and president (1956-1958) of the Association of Symbolic Logic. He received an honorary Sc.D. from Amherst College in 1970.

John McCarthy

John McCarthy was awarded the National Medal of Science for his fundamental contribution to computer science and artificial intelligence, including the development of the LISP programming language, the mathematical theory of computation, the concept and development of time-sharing, the application of mathematical logic to computer programs that use commonsense knowledge and reasoning, and the naming and thus definition of the field of artificial intelligence itself.

Commentary on McCarthy's Research

The Managing Editor of *Notices* asked David Israel of SRI International to comment on Professor McCarthy's research. He responded:

John McCarthy has made fundamental contributions to both the theory and practice of computer science. More than that of any single researcher since Turing, his research has shaped ideas about Symbolic Computation. In particular, he can with some justice be said to have created and has certainly been the prime shaper of the field of artificial intelligence (AI). He coined the term artificial intelligence (1955) and organized the first major conference on AI, the Dartmouth Conference of 1956. While at MIT, he and Marvin Minsky organized and directed the Artificial Intelligence Project. In 1963, he organized the Artificial Intelligence Laboratory at Stanford University and was its director until 1980.

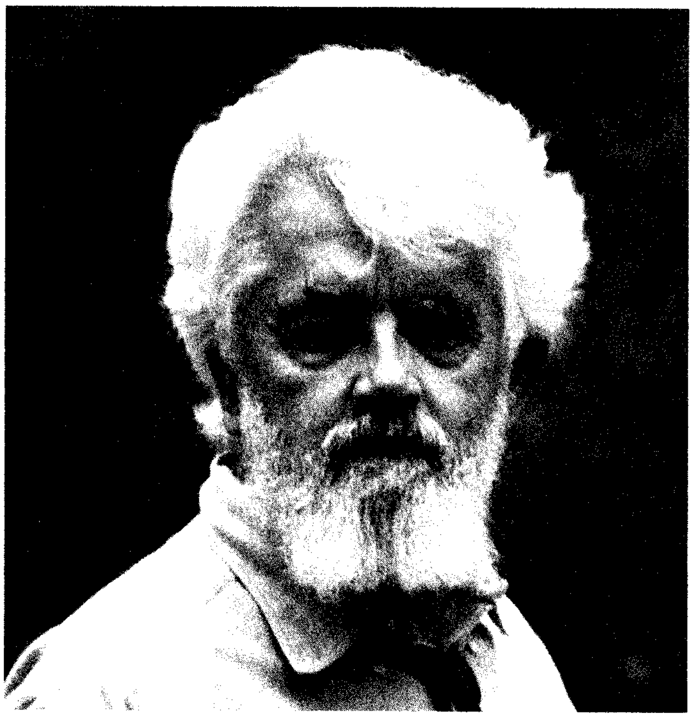

Photo courtesy of Mel Lindstrom John McCarthy

In 1958, McCarthy developed the LISP (for LISt Processor) programming language. For over 30 years, LISP has been the principal programming language in AI. The original impetus for the language was to experiment with his ideas for an "Advice Taker" (1958), a program for representing and solving problems—both mathematical and everyday, nonmathematical problems—by performing derivations in a formal language known as the situation calculus, which extends first-order languages in certain ways, e.g., by the addition of conditional expressions (of the form *IF P then a ELSE b*, where P is a formula and a and b are terms) and first-order lambda expressions as function and predicate expressions. (The use of conditional expressions is also fundamental to both the design and the analysis of LISP.) The situation calculus is still widely used for representing nonmathematical problems, especially those that can be posed as involving a single agent. At the same time that he was developing LISP, McCarthy was also a leading member of the groups that developed ALGOL 58 and ALGOL 60.

Not content with developing two of the most important high-level programming languages, McCarthy also did pioneering work in the mathematical theory of computation and the formal semantics of programming languages. In 1960, he presented both an operational semantics and a recursion theoretic analysis of LISP and proved its universality, more properly, the universality of its *apply* function. In 1966, he applied similar techniques to an analysis of a fragment of ALGOL. This work introduced a number of important ideas for proving properties of recursive programs, in particular, the use of fixed point properties to prove program equivalence by way of a rule of recursion induction. McCarthy's work on the mathematics of computation was strongly influenced by the research of another National Medalist, Professor Stephen Kleene; indeed it represented the first attempt to apply a Kleene-style framework for recursion theory, based on systems of equations defining functions, to real programming languages. During this same period (1962), McCarthy also developed the first time-sharing system. While McCarthy has continued doing important work in the mathematical theory of computation, including further research on proof rules for recursive programs (1979) and on multiprocessing versions of LISP (1984), his attention has turned increasingly to fundamental problems in Artificial Intelligence.

The "Advice Taker" was the first systematic attempt to describe and analyze what might be called a *sentential automaton*—the term itself may be McCarthy's. The central idea was that all the basic features of a problem and of the ways of solving the problem (the applicable heuristics) should be representable in a formal language. Some sentences of the language were to be treated as imperatives; these were to be obeyed. Others were declarative; these were intended to be treated as descriptions of various aspects of the problem situation. The basic cycle of the program was somehow to choose a list of declarative sentences (premises) to which to apply a deduction routine. Thus what the system knows—has been told—is represented as an axiomatic theory. The crucial point was that one did not have to write new programs as new problems were confronted; one simply told the system new things. For McCarthy, the most interesting applications were to everyday problems; this meant expressing everyday *commonsense* conceptions about familiar objects and our interactions with them, especially those conceptions involving our beliefs and knowledge, our abilities, and the preconditions and effects of our actions.

For more than 30 years, McCarthy has been pursuing, and has been urging others to pursue, the goal of a large, publicly accessible *commonsense knowledge base*, to be expressed in a logical formalism, and to be used in any one of a wide range of applications areas. Early on, it became clear to him that very few, if any, of the generalizations we use in solving everyday problems are exceptionless. That is, if they are expressed as universalized conditionals, of the form $\forall x(\Phi(x) \rightarrow \Psi(x))$, they are almost all false. Moreover, ordinary reasoning involving such nonstrict or *other things being equal* generalizations exhibits a certain *nonmonotonicity*. A set of premises Γ can be an adequate reason for concluding P, while a superset Γ' is not. Γ' might include the information that other things aren't equal. This contrasts strikingly with the structure of deductive reasoning (proof). Much of McCarthy's work since 1980 has been devoted to analyzing such reasoning. In 1977, he introduced the idea of *circumscription*, which is a rule of conjecture to be applied to first-order theories; the point of such a conjecture is that a certain predicate, or more generally, a certain formula, is to have the minimal extension consistent with the truth of the original theory. Intuitively, the conjecture is that other things are indeed equal; one can think of the strategy as minimizing exceptions or abnormalities. Adding a new axiom (premise) to the original theory may falsify the original minimization conjecture. The circumscriptive rule for a predicate occurring in a first-order theory can be thought of as resulting in a second-order theory that says explicitly that the extension of the predicate is minimal amongst the models of the original theory. A number of other formalisms for dealing with problems of *commonsense reasoning* have been introduced; but, as with LISP and the situation calculus, McCarthy's contributions in this area have maintained their central importance.

Biographical Sketch

John McCarthy was born September 4, 1927 in Boston, Massachusetts. He received his bachelor's degree from the California Institute of Technology in 1948 and his doctorate in mathematics in 1951 from Princeton University. He served as a research instructor at Princeton (1951-1953), acting assistant professor at Stanford University (1953-1955), and assistant professor at Dartmouth College (1955-1958). He then went to the Massachusetts Institute of Technology, where he advanced from assistant professor to associate professor of communications science. In 1962, he moved to his present position as professor of computer science at Stanford University. From 1965 to 1980, he was the director of the Artificial Intelligence Laboratory at Stanford.

Professor McCarthy was National Lecturer for the Association for Computing Machinery (ACM) in 1961. He received the ACM's A. M. Turing Award in 1971 and the Kyoto Prize in Advanced Technology in 1988. In 1985, he was presented with the Research Excellence Award at the International Joint Conference on Artificial Intelligence. He is a member of the American Academy of Arts and Sciences, the National Academy of Engineering, and the National Academy of Sciences.

Patrick Suppes

Patrick Suppes was awarded the National Medal of Science for his broad efforts to deepen the theoretical and empirical understanding of four major areas: the measurement of subjective probability and utility in uncertain situations, the development and testing of general learning theory, the semantics and syntax of natural language, and the use of interactive computer programs for instruction.

Patrick Suppes

Commentary on Suppes' Research

The Managing Editor of *Notices* asked Woodward Bledsoe of the University of Texas at Austin to comment on Professor Suppes' research in the use of interactive programs for instruction. He responded:

Pat Suppes has used *interactive theorem proving* in an important way for the last twenty-seven years, as a part of a series of self-paced courses given at Stanford for a large number of gifted young students. He has been the driving force in developing and testing a number of computer programs which enable the students to learn parts of mathematics by independent study, for classes in logic, set theory and calculus. Their Interactive theorem prover is a crucial part of such a program, enabling the student to give the essence of a proof (strategy), leaving the computer to fill in the details and certify the correctness. There are other well-known provers (such as the Boyer-Moore theorem prover, *A Computational Logic*, Academic Press) which are used extensively to proof-check mathematical proofs, but the Suppes programs are unique in their role as a tool for individual teaching of mathematics.

Concerning his course on Set Theory, which they began in 1974, Suppes said, "The main problem was how to develop interactive proof machinery that a computer-naive student could use to prove formally the theorems ... . Formal elementary proofs in the style of elementary logic are not feasible because of their length. Beyond the natural system of deduction ... we added a resolution theorem prover to bridge the formal gap in intuitively obvious steps, and a

Boolean decision procedure." That course involves the proof of about 650 theorems in set theory from his 1960 textbook, *Axiomatic Set Theory* (Van Nostrand, 1960; Reprinted 1972, Dover), including the classic Schröder-Bernstein theorem, and covers about the same material as his course at Stanford.

Learning to do mathematical proofs seems to be well suited to the kind of systems that the Suppes group have developed and tested so extensively. This concept will become more prominent as new tools emerge for interaction with the computer, such as being able to write proofs with a stylus in an informal manner. Suppes' contributions to this area are foundational.

The Managing Editor of *Notices* asked R. Duncan Luce of the University of California at Irvine to comment on Professor Suppes' research in the measurement of subjective probability and utility in uncertain situations, and in the development and testing of general learning theory. He responded:

Suppes' contributions to the axiomatic study of measurement are of four main types. First, he more than anyone else initiated the approach of modeling measurement systems as ordered relational structures having representations in familiar mathematical structures, such as the real numbers and various analytic geometries. Issues of meaningful measurement propositions were then cast in terms of invariance under alternative representations, and so explicit existence and uniqueness results become important. Specific early examples of such work included his improvement on Hölder's axiomatization of additive binary operations, an axiomatization of a difference representation, and modified models of subjective expected utility.

Second, his developing involvement in empirical testing of measurement axiomatizations led him to focus on finite structures. He worked out some special cases of equally-spaced structures, but an important paper with D. Scott showed it to be impossible to axiomatize broad classes of finite additive structures using a fixed finite set of universal axioms. Among positive results, he showed that finite semiorders always have a representation with a fixed threshold function.

Third, he has long been concerned with the axiomatization of probability. He was strongly motivated by the fact that the single most important theory of physics, quantum mechanics, includes a version of probability different in important respects from the widely accepted axiomatization of Kolmogorov. In a series of papers, he devised a system more suited to quantum mechanics. He has also focused on the issue that, in many real-world situations, uncertainty lacks the precision of the classical theories. Often collaborating with M. Zanotti, he has related upper and lower probability concepts to a number of other axiomatic concepts including semiorders, Scott's axiom schema for additive representation, and Choquet's concept of capacity. Other works of theirs treat random variables as the primitive and probability is inferred indirectly, and they arrive at random variable representations by treating information about moments as primitive.

Fourth, he has carried out axiomatic work on a number of relatively complex systems of scientific interest. These include classical and relativistic mechanics and various geometric systems, particularly those of interest in visual perception.

Finally, through various chapters, encyclopedia articles, and a three volume work (with D.H. Krantz, R.D. Luce, and A. Tversky) *Foundations of Measurement*, he is a major expositor of the field.

A second field to which he has contributed is learning theory. This has included three major facets, of which only the first is primarily mathematical: the formal axiomatic foundations of two classes of learning models, a very extensive series of detailed empirical studies on learning by children that underlay the last topic, the creation of very elaborate and sensitive computer-aided instruction programs (the intellectual basis of his Silicon Valley spin-off, the Computer Curriculum Corporation, which develops and sells CAI systems).

During the 1950s and 1960s two major classes of Markovian learning theories—operators acting on probability response vectors and stimulus sampling models leading to Markov chains—were under active investigation and empirical study. (The former are now found in many AI programs.) He and W. K. Estes developed very general axiomatic formulations of each type, and he generalized these models to the case of a continuum of responses. Further, contrary to some of the claims being made by linguists, he argued that such systems exhibit a degree of flexibility sufficient to account for those aspects of language learning that can be modeled by finite automata. This result was controversial.

The Managing Editor of *Notices* asked Stanley Peters of Stanford University to comment on Suppes' research in semantics and syntax of natural language. He responded:

Suppes' applications of mathematics to social sciences included analysis of language. He initiated the investigation of probabilistic phrase structure grammars—associating a probability with each rule of a grammar—and studied the feasibility of choosing the best grammar for a language on the basis of statistical fit to empirically observed corpora.

His interest in classical model theory for semantic analysis of natural language led him to investigate alternatives that were, on the one hand, simpler and easier to study mathematically and, on the other, better able to capture subtleties of meaning that are absent from the regimented languages of logic. In the first vein, he introduced the use of relational algebras to analyze quantified statements of English by more elementary means than are employed for first-order logic with its variables and quantifiers. He expanded his interest in formal reasoning, using such simple systems of restricted generality and considerable power to investigate logical argument in natural language.

In the second vein, he defined various notions of congruence in meaning, showing how these provide a graded concept of synonymy. He investigated the relationship of procedural semantics, as employed in computer science, to model theory, drawing on his notions of meaning congruence.

Suppes also considered language learning in the framework of mathematical learning theory. He showed how finite-state automata (such as McCullough-Pitts neural nets, finite-state stationary Markov processes, or Rabin and Scott automata) could be learned by reinforcement of responses to stimuli and suggested controversially that this explains a great deal of human verbal behavior.

Biographical Sketch

Patrick Suppes was born March 17, 1922 in Tulsa, Oklahoma. He received his bachelor's degree in 1943 from the University of Chicago and his doctorate in philosophy from Columbia University in 1950. He then moved to Stanford University, where he has remained ever since. He is currently Lucie Stern professor of philosophy, and professor by courtesy, of statistics, psychology, and education. From 1967 to 1990 he also served as president of the Computer Curriculum Corporation in Palo Alto, California.

Suppes was a Fellow at the Center for Advanced Study of Behavioral Science (1955-1956) and a National Science Foundation Fellow (1957-1958). He has also served as director of the Institute of Mathematical Studies in the Social Sciences at Stanford since 1959. In 1972, he received the Distinguished Scientific Contributor Award of the American Psychological Association. He is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences, and served as president of the American Educational Research Association (1973-1974). He has received honorary degrees from the University of Nijmegen in the Netherlands and from the Académie de Paris, Université René Descartes (Université de Paris V).