COMPLEXITY, INFORMATION, AND DESIGN:

A CRITICAL APPRAISAL

A Symposium sponsored by the
JOHN TEMPLETON FOUNDATION

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Purpose

The twentieth century has witnessed major advances in the sciences of the very large and very small. As the twenty-first century dawns, a new scientific frontier is opening up — the science of the very complex. Discoveries in this field promise to have implications at least as sweeping as those in cosmology and subatomic particle physics. To explore the broader issues raised by recent research into complex systems, in particular their impact on our world view and the perception we have of our place in nature, eleven scientists, theologians, and philosophers, who have focused on algorithmic, computational, and gravitational complexity as well as on questions of meaning and purpose, meet in Santa Fe under the aegis of the John Templeton Foundation. In a landscape shaped by cataclysmic natural forces and a mix of cultures, they consider what light studies of the highly complex interactions taking place in systems composed of many individual elements may cast on the phenomenon of self-organization in nature, on "emergenticism" as a philosophical alternative to reductionism, on the scientific basis for any sort of "progressive" arrow of time to be placed alongside the degenerative second law of thermodynamics, and on the utility of applying information theory to recent attempts to explore the laws of nature for evidence of "fine-tuning" or felicitous properties. The

conversation in northern New Mexico also looks at what kinds of metaphysical/theological questions could be specifically related to and linked with complexity research and whether key issues might be formulated in a way that summarizes the present state of knowledge and provides a road map for future investigations.

Chair

Paul Davies is a British theoretical physicist, based in Australia, and the author of more than twenty-five books. He obtained a doctorate from University College, London in 1970 and was a research fellow at the Institute of Theoretical Astronomy in Cambridge until 1972, when he was appointed lecturer in mathematics at King's College, London. In 1980, he was offered the chair of theoretical physics at the University of Newcastle upon Tyne, a post he held until moving to Australia in 1990, first as professor of mathematical physics at the University of Adelaide, and then as professor of natural philosophy there until 1996. He is currently visiting professor of physics at Imperial College, London. Dr. Davies's research has been mainly in the field of quantum gravity and cosmology, topics on which he has published more than one hundred scientific papers. His books, *The Physics of Time Asymmetry* (1974) and *Quantum Fields in Curved Space* (1981), written with former student Nicholas Birrell, remain standard texts for researchers. He has made several important contributions to the theory of black holes and cosmological models. His interests, however, extend much more widely, ranging from particle physics to astrobiology to complexity theory. For many years he has explored the philosophical consequences of the latest ideas at the forefront of research, work for which he won the 1995 Templeton Prize for Progress in Religion. Dr. Davies has a strong commitment to bringing science, and its deeper implications, to the wider public. In addition to the research and writing that has led to his best-selling books, he makes almost daily media appearances and contributes regularly to newspapers and journals around the world. He was for several years a columnist for *The Economist and The Australian*. He devised and presented a highly successful series of science documentaries on BBC Radio 3, two of which were published in book form as *The Ghost in the Atom* (1986) and *Superstrings: A Theory of Everything?* (1988). Recently his two television series, "The Big Questions" and "More Big Questions," won critical acclaim when screened on Australia's SBS channel. In the UK, Dr. Davies' Templeton Prize was the subject of an Equinox documentary on Channel 4, and three years ago an entire episode of Border Television's series "The Beatitudes" was devoted to an interview with him on science and the meaning of life. Dr. Davies is a fellow of the Institute of Physics, the Australian Institute of Physics, The World Economic Forum, and the World Academy of Arts and Science. He is a consultant to several publishers, as well as a number of scientific and cultural organizations in the UK and Australia. His most recent book, *The Fifth Miracle: The Search for the Origin of Life*, was published by The Penguin Press and Simon & Schuster in 1998. In it, he examines the state of our knowledge about information-based complexity, argues that science also must account for the source of biological information, and suggests that emergent laws of complexity offer reasonable hope for better understanding not only of biogenesis but of biological evolution, too.

Participants

Charles H. Bennett is a senior scientist at IBM's Thomas J. Watson Research Center in Yorktown Heights, New York, where he has worked for more than twenty-five years on aspects of the relation between physics and information. In 1973, building on the work of IBM's late Rolf Landauer, he showed that computation can in principle be performed at arbitrarily little energy cost. Eleven years later, with Professor Gilles Brassard of the University of Montreal, he invented quantum cryptography, a technique using single photons of light to send secret messages with the assurance that no one has eavesdropped on them. In 1993, Dr. Bennett and five other scientists discovered "quantum teleportation," an effect (since confirmed by laboratory experiments) allowing the exact state of a photon or other quantum particle to be disembodied from that particle and later transferred to another particle that has never directly interacted with the first particle. The main practical application of quantum teleportation is likely to be in the design of quantum computers and communications systems. Over the years, Dr. Bennett has attempted to characterize in mathematical terms the difference between complex objects, such as the human body or a Beethoven symphony, and simple ones, like a perfect crystal or ideal gas. According to him, a complex, or "logically deep," structure is one requiring a lot of computational effort to compute from any simple, non-redundant description. Complex objects, in other words, contain internal evidence of having undergone a long causal or evolutionary process to arrive at their present condition. A graduate of Brandeis University where he received his bachelor's degree in chemistry in 1964, Dr. Bennett earned his doctorate from Harvard University in 1970 for computer simulations of molecular motion. He continued his research at the Argonne National Laboratory before joining IBM in 1972. He has been a visiting professor of computer science at Boston University, a visiting scientist at the Massachusetts Institute of Technology Laboratory for Computer Science, and a Sherman Fairchild Scholar at the California Institute of Technology. A member of the National Academy of Sciences and an IBM Fellow, Dr Bennett has published some eighty research papers.

A self-taught mathematician, Gregory Chaitin was a teenager in the mid-1960s when he proposed algorithmic information theory (independently but at the same time as Andrei Kolmogorov in the Soviet Union), which combines, among other elements, Claude Shannon's information theory and Alan Turing's theory of computability and holds that the complexity of a system can be represented by the shortest computer program describing it. He subsequently became the principal architect of the developing theory of algorithmic complexity. As described in The *Limits of Mathematics* (1998), Mr. Chaitin's work suggests that the incompleteness phenomenon discovered by Kurt Gödel is much more widespread and serious than anyone had hitherto suspected, that is, he shows that there is no way to determine the answer for certain problems dealing with whole numbers because the answer is random in the sense that it requires more information to resolve than is present in arithmetic. His ideas, represented by a class of what he calls Omega numbers, have provided a theoretical underpinning for a new view of mathematics as an experimental science. A New Yorker with an Argentinean background,

Mr. Chaitin graduated from the Bronx High School of Science and studied at City University of New York. In 1966, he joined IBM in Argentina and nine years later became a member of the research staff at IBM's Thomas J. Watson Research Center in Yorktown Heights, New York, where he is currently a senior research scientist. A member of the IBM Academy of Technology, Mr. Chaitin was awarded an honorary doctorate in science by the University of Maine, Orono. He has taught there and at the Rovaniemi Institute of Technology in Finland. In 1998, he was named a visiting professor at the University of Buenos Aires. The author of some seventy research papers and five books, he wrote his latest volume, The *Unknowable* (Springer- Verlag, 1999), to place his highly original insights into a historical context for the general reader.

William A. Dembski, a mathematician and a philosopher, is visiting associate professor in conceptual foundations of science at Baylor University and a fellow at the Center for the Renewal of Science and Culture at the Discovery Institute in Seattle. He recently became director of Baylor's Michael Polanyi Center, a research group that focuses on complexity and information theory and their implications for religious belief. Dr. Dembski previously taught at the University of Chicago, Cornell, the University of Illinois at Chicago, Northwestern, the University of Notre Dame, and the University of Dallas. A graduate of the University of Illinois at Chicago where he earned a B.A. in psychology, a M.S. in statistics, and a Ph.D. in philosophy, he also received a doctorate in mathematics from the University of Chicago in 1988 and a master of divinity degree from Princeton Theological Seminary in 1996. He has held National Science Foundation graduate and postdoctoral fellowships and recently won a Templeton Foundation research grant to explore the constructive interacton between science and religion. Dr. Dembski is the author of some thirty-five articles published in mathematical, philosophy, and theology journals and three books. *In The Design Inference: Eliminating Chance Through Small Probabilities* (1998), he examines the design argument in a post-Darwinian context and analyzes the precise connections linking chance, probability, and intelligent causality. A forthcoming volume, *Intelligent Design: The Bridge Between Science and Theology*, will be published next month by InterVarsity Press.

A theologian who writes often about the intersection of science and religion, Niels Henrik Gregersen is an associate professor of systematic theology on the Faculty of Theology at the University of Aarhus and an ordained minister of the Evangelical-Lutheran Church of Denmark. He recently published an influential paper on complexity in the journal *Zygon*. Dr. Gregersen graduated from the Haderslev Cathedral School and the University of Copenhagen where he earned his Ph.D. in 1987. He began his academic career as an assistant professor in ethics and philosophy of religion at Aarhus, and for the past six years, he has served as assistant pastor of the university's Church of St. John in addition to teaching and writing. The author of three books and more than fifty major articles in Nordic, German, and English, Dr. Gregersen serves as vice president of the European Society for the Study of Science and Theology and as a member of the Theological Commission of the Church of Denmark's Council on Inter-Church Relations. He is general editor of *Studies in Science and Theology* and systematic-theological editor of the *Danish Journal of Theology*, as well as a member of the editorial advisory board of *Zygon* and a member of the editorial council of *Dialog: A Journal of Theology*. A former member of the editorial board of the Danish publisher ANIS and currently co-editor of *Complementa*, a book series published by the University of Aarhus Press, he has inaugurated a new series, *Issues in Science and Theology*, which will be published in Scotland by T & T Clark and in the United States by W. B. Eerdmans.

Since 1992, Dr. Gregersen has been a leader of the Danish Forum for Science and Theology. He recently was awarded a Templeton Foundation research grant for exploring the constructive interaction of science and religion.

Stuart A. Kauffman, a biologist, is a pioneer in the field of complexity theory. While still a graduate student, he began testing his ideas about the origins of life by simulating the interaction of various abstract agents — representative of chemical and biological substances — on computers. He concluded that upon reaching a certain level of diversity, a system of simple chemicals undergoes a dramatic transformation, similar to a phase change in physics, whereby molecules spontaneously combine to create larger, more complex molecules with catalytic capability leading to the formation of collectively autocatalytic sets of molecules. If so, life may be an expected property of complex chemical systems. His theory led him to the further hypothesis that complex arrays of interacting genes, which turn one another on and off, do not behave randomly but tend to converge toward a relatively small number of recurring patterns that exhibit stunning degrees of order. In *The Origins of Order: Self Organization and Selection in Evolution* (1993), Dr. Kauffman proposed that the principle of self-organization may have played a larger role than natural selection in shaping the development of life on Earth. On a practical level, his ideas about what is sometimes called "molecular diversity" helped spawn a field known as combinational chemistry. The new field is revolutionizing drug development by making it possible to create and sift through vast quantities of potential drug ingredients with lightening speed. Holder of nine patents, Dr. Kauffman is the founding general partner (with Ernst & Young) of Bios Group LP, a company that seeks to apply biological theories to business. He began his career as an assistant professor of biophysics and theoretical biology at the University of Chicago then taught for twenty years at the University of Pennsylvania School of Medicine, where he is now emeritus professor of biochemistry and biophysics, before moving to the Santa Fe Institute. He was a professor there for more than a decade and now serves on the Institute's board of trustees and its scientific advisory board. A Phi Beta Kappa graduate of Dartmouth College, Dr. Kauffman studied philosophy at Oxford University on a Marshall Scholarship and took his M.D. in 1968 at the University of California/San Francisco Medical School where he won the Borden Prize for Research. The recipient of many other awards, he held a John D. and Catherine T. MacArthur Fellowship, the so-called "genius prize," from 1987 to 1992 and won the American Cybernetic Society's Weiner Gold Medal in 1971 and the Gold Medal of the Italian Accademia Nazionale dei Lincea in 1997. The former co-chief editor of the *Journal of Theoretical Biology*, Dr. Kauffman has served on the editorial boards of a number of other journals. He was president of the Society for Mathematical Biology in 1990-91 and presently serves as a consultant to the Los Alamos National Laboratory and to Affymax Research Institute. Dr. Kauffman is the author of more than 110 scientific papers and three books. In *At Home in the Universe: The Search for Laws of Self-Organization and Complexity* (1996), he spelled out the implications of his theories on biological evolution as he showed how order emerges naturally — and possibly even necessarily — out of chaos. His most recent volume, *Investigations*, deals with his latest theory of complexity and will be published later this year by Oxford University Press.

An assistant professor of biology at Princeton University since 1994, Laura Landweber explores the origin, function, and potential uses of biological information. Her current research focuses on the evolution of complex genetic systems, including gene unscrambling and RNA editing

in unicellular organisms. Her work also uses experimental evolution as a tool for understanding the origins of RNA catalysis and the genetic code and as an approach to building computers out of biological molecules like DNA and RNA. With colleagues, she has developed a model for the guided homologous recombinations that take place during gene rearrangement in ciliates and demonstrated that such a model has the computational power of a Turing machine, the accepted formal model of computation. A graduate of Princeton, where she majored in molecular biology and was elected to Sigma Xi, Dr. Landweber went on to study cellular and developmental biology at Harvard, where she was elected a junior fellow of the Harvard University Society of Fellows and received a Ph.D. in 1993. Her subsequent honors have included National Science Foundation and NIH grants and Burroughs Wellcome Fund and Sigma Xi Young Investigator Awards. She recently became a fellow-at-large of the Santa Fe Institute. Dr. Landweber is the author of more than forty research papers and the editor of four books, including *Evolution as Computation* (with E. Winfree), which will be published by Springer- Verlag later this year and focuses on the interface between computer science and biology.

Werner R. Loewenstein has won world renown for his discoveries in cell communication and biological information transfer. Currently the director of the Laboratory of Cell Communication at the Marine Biological Laboratory in Woods Hole, Massachusetts, he is also professor and chairman emeritus of physiology and biophysics at the University of Miami School of Medicine. Dr. Loewenstein formerly served as professor of physiology and director of the Cell Physics Laboratory at Columbia University's College of Physicians and Surgeons. A native of Germany, he did his undergraduate and graduate studies in physics and physiology at the University of Chile in Santiago. He taught at his alma mater for three years and did post-graduate work in biophysics and neurobiology at the Wilmer Institute of The Johns Hopkins University and at the University of California/Los Angeles before joining the Columbia faculty in 1957. He was named professor and chairman of physiology and biophysics at the University of Miami in 1971. Dr. Loewenstein is editor-in-chief of the *Journal of Membrane Biology* and was formerly editor of *Biochimica Biophysica Acta*. He served on President Ford's Biomedical Research Advisory Board. A Fulbright Distinguished Professor at the University of Berlin in 1970, he has given endowed lectures at the University of Chicago, the Royal Swedish Academy of Sciences, the University of Tübingen, the College de France, the Russian Academy of Sciences in Moscow and St. Petersburg, Konstanz University, and the University of Munich, as well as numerous plenary and keynote addresses at international scientific congresses. He is the author of more than 250 research articles and several books in the fields of biophysics, neurobiology, and information theory and cell communication. His most recent book, *The Touchstone of Life*, published earlier this year by Oxford University Press, summarizes our knowledge of the long-hidden world of molecular information and considers the implications for our understanding of the origin of life and consciousness.

An experimental biologist, Harold J. Morowitz is the Clarence Robinson Professor of Biology and Natural Philosophy at George Mason University and a member of its Krasnow Institute for Advanced Study. He formerly taught for thirty-three years at Yale University where he was a professor of molecular biophysics and biochemistry and, from 1981 to 1986, master of Pierson College. Dr. Morowitz earned his B.S. degree in physics and philosophy at Yale in 1947 and his Ph.D. in biophysics in 1951. He spent the next two years as a biophysicist at the Natural Bureau of Standards and then at the National Heart Institute of the National Institutes of Health before returning to his alma mater as an assistant

professor in 1955. He has been a visiting professor at the University of Hawaii and the University of California/Berkeley and a visiting scientist in the exobiology section of the National Aeronautics and Space Administration. Dr. Morowitz joined the George Mason faculty in 1988 and served as director of the Krasnow Institute from 1993 to 1998. A fellow of the American Association for the Advancement of Science and a member of Phi Beta Kappa and Sigma Xi, he is a charter member of the Biophysical Society as well as a member of the American Institute of Biological Sciences. Currently editor-in-chief of the journal *Complexity* and on the editorial boards of *Biology and Philosophy and Computational Biology*, he is the author of some 130 research papers and fourteen books. His work deals with the thermodynamics of living systems, as well as the relation of science to society. Two volumes of continuing influence, *Beginnings of Cellular Life: Metabolism Recapitulates Biogenesis* (1992) and *Cosmic Joy and Local Pain* (1987), examine the critical passages from inanimate matter to life and from life to consciousness. Dr. Morowitz has described himself as a "mystical scientist," and he sees within the workings of the biological and geological universes "a plan or cosmic intelligence that somehow had us in mind." His latest collection of essays, *The Kindly Dr. Guillotine*, was published by Counterpoint in 1997.

Arthur Peacocke devoted the first twenty-five years of his career to teaching and research in the field of physical chemistry, specializing in biological macromolecules and making significant contributions to our understanding of the structure of DNA. His principal interest during the past twenty-five years has been in exploring the relation of science to theology. After going to Oxford, where he was a scholarship student at Exeter College, he worked in the Physical Chemistry Laboratory, with Nobel laureate Sir Cyril Hinshelwood, and earned a D. Phil. in physical biochemistry in 1948. For the next eleven years, he taught at the University of Birmingham and then returned to Oxford as a fellow and tutor at St. Peter's College from 1959 to 1973. In addition to publishing more than 125 papers and three books in his field, he served as editor of *Biopolymers, the Biochemical Journal*, ries of monographs on physica biochemistry published by Oxford Universi. While lecturing at Bi mingham, Dr. Peacocke also had studied theologwas ordained a priest i the Church of England in 1971. He went on to sdean, and as a fellow, of Clare College, Cambridge, for eleven years. In became founding dire tor of the Ian Ramsey Centre at St. Cross College, a position he held u til 1988. To oversee the administration of a grant Johnn Templeton Found tion, he resumed the directorship of the Centre, w dies issues in the relation of theology to science, from 1995 to 1999. A fou the Sc ence and Religion Forum in the United Kingdom, of the corresponcein society (ESSSAT), and of the Society of Ordained Scientists, a new dispersed religious order, he was honorary chaplain of Christ Church Cathedral, Oxford, from 1989 to 1996 and is now an honorary canon. Dr. Peacocke has been awarded the senior degree of D.Sc. as well as a D.D. by Oxford and honorary degrees from Georgetown University and De Pauw University. He was made a member of the Order of the British Empire by Queen Elizabeth II in 1993. The author of nine books exploring the relationship between science and religion, his most recent studies are *From DNA to Dean: Reflections and Explorations of a Priest-Scientist* (Canterbury Press, 1996) and *God and Science: A Quest for Christian Credibility* (SCM Press, 1996).

Ian Stewart, the director of the Mathematics Awareness Centre at Warwick University, is a professor of mathematics at Warwick and at the Royal Institution, London. Widely known

for his popular writing and broadcasting on mathematical themes, he was awarded the Royal Society's Michael Faraday Medal for furthering public understanding of science in 1995. He is also an active research mathematician who has published more than 120 papers in scientific journals. A graduate of Cambridge University, Dr. Stewart earned his Ph.D. at Warwick in 1969. After fifteen years as a lecturer there, he became a reader in 1984 and a professor in 1990. He has been a Humboldt Fellow at the University of Tübingen, a visiting fellow at the University of Auckland, and a visiting professor at the University of Connecticut, Southern Illinois University, and the University of Houston. He held the Gresham Professorship of Geometry at Gresham College from 1994 to 1998, and in 1998, he also was awarded an honorary degree from the University of Westminster. Dr. Stewart has been the recipient of numerous research grants and given many invited addresses. A member of the advisory board of *Mathematical Horizons* and of the editorial boards of *Dynamics and Stability* and the *International Journal of Bifurcation & Chaos*, he is the author of some sixty books. His acclaimed 1996 volume, *Nature's Numbers*, was shortlisted that year for the RhÔne-Poulenc Prize for Science Books. His most recent book, *The Science of Discworld* (1999), with best-selling science-fiction author Terry Pratchett and biologist Jack Cohen, uses fantasy to explore modern science. Dr. Stewart is the mathematics consultant for the *New Scientist* and writes the monthly "Mathematical Recreations" column for *Scientific American*.

The Chambered Nautilus

- Oliver Wendell Holmes

This is the ship of pearl, which, poets feign,
Sails the unshadowed main,—
The venturous bark that flings
On the sweet summer wind its purpled wings
In gulfs enchanted, where the Siren sings,
And coral reefs lie bare,
Where the cold sea-maids rise to sun their streaming hair.

Its webs of living gauze no more unfurl;
Wrecked is the ship of pearl!
And every chambered cell,
Where its dim dreaming life was wont to dwell,

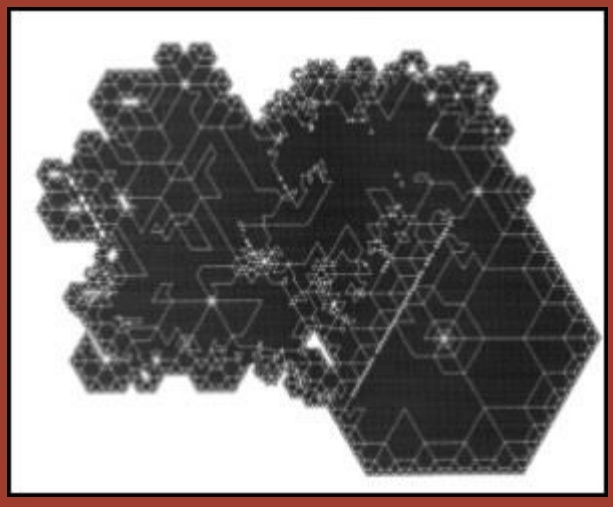
As the frail tenant shaped his growing shell,
Before thee lies revealed,—
Its irised ceiling rent, its sunless crypt unscaled!

Year after year beheld the silent toil
That spread his lustrous coil;
Still, as the spiral grew,
He left the past year's dwelling for the new,
Stole with soft step its shining archway through,
Built up its idle door,
Stretched in his last-found home, and knew the old no more.

Thanks for the heavenly message brought by thee,
Child of the wandering sea,
Cast from her lap, forlorn!
From thy dead lips a clearer note is born
Than ever Triton blew from wreathed horn!
While on mine ear it rings,
Through the deep caves of thought I hear a voice that sings:—

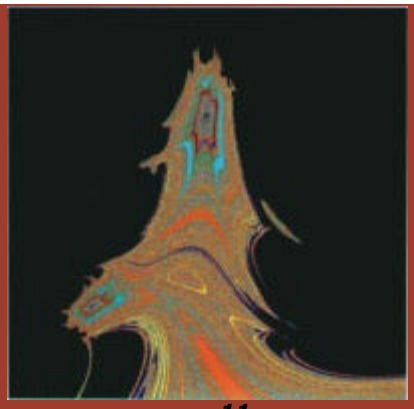
Build thee more stately mansions, O my soul,
As the swift seasons roll!
Leave they low-vaulted past!
Let each new temple, nobl er than the last,
Shut thee from heaven with a dome more vast,
Till thou at length art free,
Leaving thine outgrown shell by life's un- resting sea!

Paterson's Worm

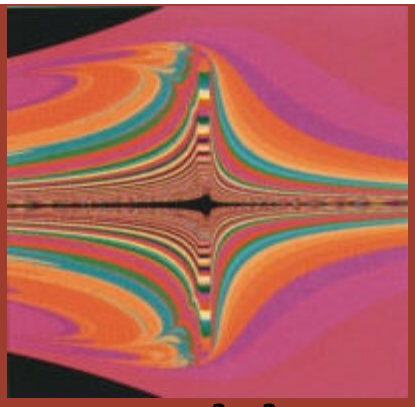


Paterson's Worm, a hypothetical creature, crawls around on an infinite grid of "streets." Like Hansel and Gretel, the worm marks its path as it goes. It never reuses a street, and whenever it enters an intersection, the worm decides which way to go by innate rules, always making the same choice when it faces the same pattern of used and unused thoroughfares. Different species of worms have different rules: some go on forever; others "paint themselves into a corner" of intersecting streets, all of which they have previously used, and die because they have exhausted their options. The "streetscape" pictured above reflects a growth process that becomes more and more complicated by building on the foundations of its earlier, simpler stages. Navigating it successfully daunts all but the wisest worms.

Fractals



$f(z) = z^{11} + c$



$f(z) = \exp(x^2/y^2) + y + c$

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