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note: because important websites are frequently "here today but gone tomorrow", the following was archived from <http://superstringtheory.com/history/history1.html> on February 4, 2004. This is NOT an attempt to divert readers from the aforementioned website. Indeed, the reader should only read this back-up copy if it cannot be found at the original author's site.

A Timeline of Mathematics and Physics

- 1500 **Babylonians** establish the metric of flat 2-dimensional space by observation in their efforts to keep track of land for legal and economic purposes.
- 518 **Pythagoras** -- a Greek educated by mystics in Egypt and Babylon -- founds community of men and women calling themselves *mathematikoi* in southern Italy. They believe that reality is in essence mathematical. Pythagoras noted that vibrating lyre strings with harmonious notes have lengths that are proportional by a whole number. The Pythagorean theorem proves by reasoning what the Babylonians figured out by measurement 1000 years earlier.
- 387 **Plato** -- after traveling to Italy and learning about the Pythagoreans -- founds his Academy in Athens and continues to develop the idea that reality must be expressible in mathematical terms. But Athens at that time has developed a notoriously misogynist culture. Unlike his role model Pythagoras whose school developed many women *mathematikoi*, Plato does not allow women to participate.
- 300 **Euclid** of Alexandria, a gifted teacher, produces [Elements](#) -- one of the top mathematics textbooks of recorded history which organizes the existing Mediterranean understanding of geometry into a coherent logical framework.
- 225 Ionian mathematician **Apollonius** writes [Conics](#) and introduces the terms "ellipse", "parabola", and "hyperbola" to describe conic sections.
- 140 Nicaean mathematician and astronomer **Hipparchus** develops what will be known as trigonometry.
- 150 **The Almagest** by Alexandrian astronomer and mathematician **Claudius Ptolemy** asserts that the Sun and planets orbit around the Earth in perfect circles. Ptolemy's work is so influential that it will become official church doctrine when the Christians later come to rule Europe.
- 415 As a glorious 2000 years of ancient Mediterranean mathematics and science comes to a close, **Hypatia** of Alexandria -- a renowned teacher, mathematician, astronomer, and priestess of Isis -- is kidnapped from a public religious procession and brutally murdered by a mob of angry Christian monks.
- 628 Hindu mathematician-astronomer **Brahmagupta** writes [Brahma- sphuta- siddhanta](#) (The Opening of the Universe). Hindu mathematicians develop numerals and start investigating number theory.

- 830** The spread of Islam leads to the spread of written Arabic language. As ancient Greek and Hindu works are translated into Arabic, a culture of mathematics and astronomy develops. The peak of this cultural flowering is represented by Arabic mathematician **Al-Khwarizmi**, working at the House of Wisdom in Baghdad, who develops what will be known as algebra in his work *Hisab al-jabr w'al-muqabala*.
- 1070** Iranian poet, mathematician, and astronomer **Omar Khayyam** begins his Treatise on Demonstration of Problems of Algebra, classifying cubic equations that could be solved by conic sections. Khayyam was such a brilliant poet that History has nearly forgotten that he was also a brilliant scientist and mathematician. *The moving finger writes...*
- 1120** **Adelard of Bath** translates works of Euclid and Al-Khwarizmi into Latin and introduces them to European scholars.
- 1482** Euclid's Elements is published using the revolutionary new technology of the printing press, leading to a revolution in education and scholarship as information becomes more difficult for authorities to control.
- 1543** **Copernicus** publishes De revolutionibus orbium coelestium (On the revolutions of the heavenly spheres) asserting that the Earth and planets revolve about the Sun. The Catholic Church has accorded an official holy status to Ptolemy's geocentric Universe. Copernicus avoids prosecution as a heretic by waiting until the end of his own life to publish his controversial claims.
- 1589** Pisa University mathematics instructor **Galileo Galilei** studies the motion of objects and begins a book De Motu (On Motion) which he never finishes.
- 1602** **Galileo** observes that the period of a swinging pendulum is independent of the amplitude of the swing.
- 1609** **Johannes Kepler** claims in the journal Astronomia Nova that the orbit of Mars is an ellipse with the Sun at one focus and sweeps out equal areas in equal time. He will later generalize these into his famous Three Laws of Planetary Motion.
- 1609** **Galileo** makes his first telescope. His observations of the Moon show that it looks like a very large lumpy rock -- not a divinely smooth and perfect shining Platonic heavenly orb. This discovery has enormously distressing cultural reverberations for Western culture and religion.
- 1614** Scottish theologian **John Napier** (who does mathematics as a hobby) publishes his discovery of the logarithm in his work Mirifici logarithmorum canonis descriptio.
- 1615** Kepler's mother Frau Katharina Kepler is accused of witchcraft by a local prostitute. European witch-hunting was at its peak during Kepler's career. And witch-hunting was supported by all levels of society including secular officials and intellectuals in universities. Kepler spends the next several years making legal appeals and hiding his mother from legal authorities seeking to torture her into confessing to witchcraft. Examining an accused witch *ad torturam* was a standard court procedure during this era.
- 1620** Under court order, Kepler's mother is kidnapped in the middle of the night from her daughter's home and taken to prison. Kepler spends the next year appealing to the Duke of Württemberg to prevent his imprisoned mother from being examined *ad torturam*.

- 1621** On September 28, Katharina Kepler is taken from her prison cell into the torture room, shown the instruments of torture, and ordered to confess. She replies "*Do with me what you want. Even if you were to pull one vein after another out of my body, I would have nothing to admit,*" and says the Lord's Prayer. She is taken back to prison. She is freed on October 4 upon order of the Duke, who rules that her refusal to confess under threat of torture proves her innocence. He also orders her accusers to pay the cost of her trial and imprisonment.
- 1622** After having spent most of the last 7 years under the legal threat of imminent torture, Katharina Kepler dies on April 13, still being threatened with violence from those who insist she is a witch.
- 1624** Pope Urban VIII promises Galileo that he is allowed write about Copernican heliocentrism if he treats it as an abstract proposition.
- 1628** Kepler uses Napier's logarithms to compute a set of astronomical tables (*the Rudolphine Tables*) whose accuracy is so impressive that it leads to the quiet acceptance of the heliocentric solar system by everyone in the shipping industry.
- 1629** Basque mathematician **Pierre de Fermat** -- the founder of modern number theory -- begins his brilliant career by reconstructing the work of Apollonius on conic sections. Fermat and Descartes pioneer the application of algebraic methods to solving problems in geometry.
- 1632** Galileo publishes Dialogue concerning the two greatest world systems, which argues convincingly for the Copernican view that the Earth and planets revolve around the Sun.
- 1633** The Inquisition calls Galileo to Rome to answer charges of heresy against the Catholic Church.
- 1637** Descartes publishes his revolutionary Discours de la méthode (Discourse on Method) containing 3 essays on the use of reason to search for the truth. In the third essay, Descartes describes analytic geometry and uses the letters (x,y,z) for the coordinate system that will later bear his name.
- 1642** Galileo dies at his villa in Florence, still under house arrest from charges of heresy.
- 1663** Cambridge mathematician Isaac Barrow delivers lectures on modern methods of computing tangents that inspire his student **Isaac Newton** towards developing **calculus**.
- 1665** Newton's "miraculous years" in math and physics when he discovers the **derivative** (which he sees as a ratio of velocities called *fluxions*) and the **integral** (which he sees as a fluent of the fluxions). Newton shows that the *fluent* and *fluxion* are inversely related -- a result now called the *Fundamental Theorem of Calculus*. Newton also develops his ideas on optics and gravitation. He tries to publish his work in 1671, but the publisher goes bankrupt.
- 1683** **Jacob Bernoulli** -- who studied mathematics and astronomy against the wishes of his career-minded parents -- teaches Newtonian mechanics at the University of Basel and turns mathematical physics into a family business.
- 1684** **Leibniz** publishes the beginning of his work on **differential and integral calculus**. He discovers the Fundamental Theorem of Calculus in his own way. Leibniz originates most of the current calculus notation including the integral sign. He portrays an integral as a sum of infinitesimals -- a concept rejected by Newton.

- 1687** Newton publishes Principia Mechanica after **Edmund Halley** convinces Newton to write up his alleged proof that an inverse square force law leads to elliptical orbits. Newton's **Laws of Motion** and **Law of Gravitation** lead to the development of theoretical physics itself. This event marks a permanent change in the relationship between human beings and the Universe.
- 1693** Newton has a nervous breakdown after his close companion **Fatio De Duillier** becomes ill and has to return to Switzerland.
- 1696** *Brachistochrone problem* solved by **Jacob** and **Johann Bernoulli** -- an early result in the calculus of variations.
- 1712** Thanks to a campaign waged by Newton, a commission appointed by Royal Society of London President Isaac Newton rules that Leibniz is guilty of plagiarism against Newton in the discovery of calculus. English mathematics and theoretical physics go into decline because those loyal to Newton are hesitant to adopt Leibniz' infinitesimal and his clean, intuitively-appealing notation.
- 1736** **Leonhard Euler** begins the field of **topology** when he publishes his solution of the Konigsberg Bridge problem.
- 1738** Hydrodynamics by **Daniel Bernoulli**
- 1748** The multi-talented **Euler** begins the fields of mathematical analysis and analytical mechanics with Introductio in analysin infinitorum. Euler introduces the formula $e^{ix} = \cos x + i \sin x$.
- 1758** **Joseph-Louis Lagrange** finds the complete general solution to the Newtonian equations of motion for a vibrating string, which explains the harmonic relations observed by Pythagoras 22 centuries ago.
- 1770** Hyperbolic trigonometry (i.e., **cosh**, **sinh**) is developed.
- 1772** **Henry Cavendish** -- a wealthy-but-paranoid recluse -- discovers that the **electrostatic force** is described by an inverse square law similar to gravity, but doesn't tell anyone in the science community.
- 1788** **Lagrange** further develops the analytical mechanics of Euler when he publishes Mécanique Analytique, revealing Newtonian mechanics to be a rich field of exploration for mathematicians.
- 1789** Aristocrat **Charles-Augustin de Coulomb** -- hiding from the French Revolution after the storming of the Bastille -- shows that the electrostatic force between electric charges was very well described by an inverse square law -- in full analogy with Newtonian gravity. This becomes known as **Coulomb's Law** even though Henry Cavendish was the first one to demonstrate it.
- 1793** Lagrange is arrested during the Reign of Terror but is rescued by **Antoine-Laurent Lavoisier**, the founder of modern chemistry. Unfortunately, Lavoisier's career in chemistry is ended when he is taken to meet "Madame Guillotine" on May 8, 1794.
- 1799** **Pierre-Simon Laplace** publishes his work Traité du Mécanique Céleste (Treatise on Celestial Mechanics) using differential equations to solve problems in planetary motion and fluid flow.

- 1807** After serving as a member of the Revolutionary Committee that terrorized France, sent Coulomb into hiding, arrested Lagrange, and guillotined Lavoisier, a repentant **Jean Baptiste Joseph Fourier** causes controversy with his memoir **On the Propagation of Heat in Solid Bodies**. His former teachers Laplace and Lagrange object to his use of infinite trigonometric series which we now call a "Fourier series". Fourier later wins the Paris Institute Mathematics Prize for solving the problem of heat propagation over the repeated objections of Laplace and Lagrange.
- 1817 Johann Karl Friedrich Gauss** begins working on non-Euclidean geometry and lays the foundations of differential geometry. But he doesn't publish because he is afraid of the controversy that would result.
- 1820** Danish physicist **Hans Christian Oersted** studied the way an electric current in a wire could move the magnetic needle of a compass, which strongly suggested that **electricity** and **magnetism** were related somehow.
- 1823** Transylvanian mathematician **János Bolyai** -- despite being warned against it by his father -- tosses out Euclid's Fifth Axiom and shows that **non-Euclidean geometry** is possible. Gauss calls him a genius of the first order, but then crushes the young man by telling him he (Gauss) discovered it years ago but failed to publish due to his own fear of controversy.
- 1826** Elliptic functions are developed by **Gauss, Jacobi, and Abel**.
- 1826** In his book **Memoir on the Mathematical Theory of Electrodynamical Phenomena, Uniquely Deduced from Experience**, **André Marie Ampère** gave a mathematical derivation of the magnetic force between 2 parallel wires with electric current -- what we now call **Ampère's Law**.
- 1827** Ohm's Law of electrical resistance is published in his book **Die galvanische Kette, mathematisch bearbeitet**.
- 1827 Augustin-Louis Cauchy** develops the calculus of residues, beginning his work in mathematics that made complex analysis one of the most important analytical tools of modern theoretical physics including *superstring* theory.
- 1828** Self-educated English mill worker George Green publishes his work on the use of potential theory to solve **partial differential equations** and develops one of the most powerful mathematical technologies in theoretical physics -- **the Green function**.
- 1829** Russian mathematician **Nikolai Ivanovich Lobachevsky** publishes his independent discovery of non-Euclidean geometry in the **Kazan Messenger**. Years later, one of his physics students will become known to history as Lenin's father.
- 1831 Evariste Galois** develops the **nascent group theory** with his work on the permutation group.
- 1831 Michael Faraday** discovers **magnetic induction** -- now known as **Faraday's Law** -- where moving magnetism creates electricity. This result increases support for the idea of a Unified Theory of electricity and magnetism.
- 1829** French mathematician **Joseph Liouville** begins to work on boundary value problems in partial differential equations, leading to Sturm-Liouville theory. He then develops the study of

conformal transformations and later proves the Liouville Theorem regarding the invariance of the measure of phase space under what will later be called **Hamiltonian flow**.

1834 William Rowan Hamilton applies his mathematical development of characteristic functions in optics to mechanics. And the enormous and potent mathematical technology of Hamiltonian dynamics is born.

1840 Karl Weierstrass begins his work on elliptic functions.

1843 After a period of emotional distress and alcohol abuse, Hamilton finally deduces the noncommutative multiplication rule for **quaternions**. His first publication on the subject is to carve the quaternion formula into a bridge.

1844 Hermann Grassmann develops exterior algebra and the Grassmannian.

1851 Bernhard Riemann submits his Ph.D. thesis to his supervisor **Gauss**. In his thesis, he describes what is now called a '**Riemann surface**' -- an essential element in understanding superstring theory. **[StealthSkater note: much more of the behind-the-scenes history is archived in the "Strings_1" file at => [doc](#) [pdf](#) [URL-doc](#) [URL-pdf](#)]**

1854 George Boole develops **Boolean logic** in **Laws of Thought**.

1871 Norwegian mathematician **Marius Sophus Lie** publishes work on Lie algebras, opening up the field of **differential topology** and paving the way for **gauge field theory** 100 years later.

1873 James Clerk Maxwell publishes a set of equations from which all of the observed laws of **electromagnetism** could be derived through mathematics. These equations turn out to have solutions that describe waves traveling through space with a speed that agrees with the measured speed-of-light.

Maxwell makes the bold conclusion that light therefore must consist of electromagnetic waves, writing that he could *"scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena."*

1874 Cantor invents set theory.

1878 William Clifford develops **Clifford algebras** from the work of Grassmann and Hamilton.

1878 Arthur Cayley writes **The Theory of Groups**, where he proved that every finite group can be represented as a group of permutations.

1883 Wilhelm Killing works on n-dimensional non-Euclidean geometry and Lie algebras. It was work that later results in the concept of a **Killing vector** -- a powerful tool in differential geometry, **quantum gauge field theory**, **supergravity**, and **string theory**.

1884 Heinrich Hertz rewrites Maxwell's Equations in a more elegant notation where the symmetry between electricity and magnetism was obvious. Hertz then creates the first **radio waves** and **microwaves** in his laboratory and shows that these electromagnetic waves behaved just as observable optical light behaved, proving that light was electromagnetic radiation as Maxwell had predicted.

- 1884 Ludwig Boltzmann** makes a theoretical derivation of blackbody radiation using Maxwell's equations and thermodynamics, confirming the 1879 result measured experimentally by Josef Stefan. Their result -- the **Stefan-Boltzmann Law** -- is not quite right, and the correct solution in the next century will mark the beginning of Quantum Theory.
- 1887 Michelson** and **Morley** measure the Earth's velocity through the "ether" to be zero, strongly suggesting that there is no ether and that **the velocity of light is the same for all observers** -- a result whose full implications have changed the World forever.
- 1894 Elie Cartan** classifies simple Lie algebras
- 1895 Henri Poincaré** publishes Analysis Situs and gives birth to the field of **algebraic topology**.
- 1897** The **electron** discovered by **J.J. Thompson**.
- 1899 Hendrik Lorentz** becomes the 3rd person after Voigt and FitzGerald to write down the relativistic coordinate transformations that will bear his name. **The Lorentz transformations** leave the speed-of-light invariant, as suggested by the Michelson-Morley experiment.
- 1899 David Hilbert's** Grundlagen der Geometrie (Foundations of Geometry) is published, putting modern geometry on a solid rigorous foundation.
- 1901 Max Planck** makes his **quantum hypothesis that energy is carried by indistinguishable units called "quanta" rather than flowing in a pure continuum**. This hypothesis leads to a successful derivation of the blackbody radiation law now called Planck's Law, although in 1901 the quantum hypothesis as yet had no experimental support. The unit of quantum action is now called Planck's constant.
- 1905** Swiss patent clerk **Albert Einstein** proposes Planck's quantum hypothesis as the physics underlying the photoelectric effect. Planck wins the Nobel Prize in 1918 and Einstein in 1921 for developing **Quantum Theory**, one of the 2 most important developments in 20th century physics.
- 1905 Einstein** publishes his simple, elegant Special Theory of Relativity, making mincemeat of his competition by relying on only two ideas: (1) The laws of physics are the same in all inertial frames, and (2) the speed -of-light is the same for all inertial observers.
- 1905 Poincaré** shows that Lorentz transformations in space and time plus rotations in space form a group which comes to be known as the **Lorentz group**. The Lorentz group plus translations in space form a group called the **Poincaré group**.
- 1907 Minkowski** publishes Raum und Zeit (Space and Time) and establishes the idea of a space-time continuum.
- 1909 Hilbert's** work on integral equations later leads to the concept of a **Hilbert space** in Quantum Mechanics.
- 1915 Emmy Noether** publishes Noether's Theorem, discovering the relationship between symmetries and conserved currents that was crucial to the later development of **quantum gauge field theory** and **string theory**.

- 1915 Einstein** -- with Hilbert in stiff competition -- publishes his stunning **General Theory of Relativity** and is lucky enough to be able to find observational support for his theory right away in the perihelion advance of Mercury and the deflection of starlight by the Sun.
- 1916** German astrophysicist **Karl Schwarzschild** -- serving on the Russian front in WWI == mails Einstein his paper on the ***Schwarzschild metric*** and Einstein presents it at a meeting of the Prussian Academy of Sciences. 6 months and another major paper later, Schwarzschild dies of illness on the front.
- 1921 Theodor Kaluza** follows Einstein's advice and publishes his highly unorthodox ideas about **unifying gravity with electromagnetism** by adding an extra dimension of space that is compactified into a small circle. **Kaluza-Klein compactification** will become a rich subject of exploration in particle theory 60 years later.
- 1925 Werner Heisenberg** shows that his quantized probability operators form a non-commutative algebra. Born and Jordan point out to him that this is a **matrix** algebra. And the matrix formulation of Quantum Mechanics is born. He gets the Nobel Prize in 1932.
- 1924 Louis de Broglie** proposes the **particle-wave duality** of the electron in his doctoral thesis at the Sorbonne. He gets the Nobel Prize in 1929.
- 1926** After learning of the work of de Broglie, **Erwin Schrödinger** develops his **wave equation version** of Quantum Mechanics and unravels its relationship to the matrix formulation of Quantum Mechanics by Heisenberg. He shares the Nobel Prize with Dirac in 1933.
- 1926** Young Cambridge math student **Paul Dirac** discovers the operator algebra behind **Heisenberg's Uncertainty Principle** for his doctoral thesis.
- 1927 Heisenberg** discovers **the Uncertainty Principle** that bears his name.
- 1928 Dirac** introduces a relativistic quantum equation for the electron -- an equation now known as the **Dirac equation**. His equation predicts the discovery of the positron, and he shares the Nobel Prize with Schrodinger in 1933.
- 1928** Werner Heisenberg, Hermann Weyl, and Eugene Wigner begin an exploration of **symmetry groups** in quantum mechanics that has far-reaching consequences.
- 1929 Edwin Hubble** -- with the help of his mule driver Humason -- observes the **redshift** of distant galaxies and concludes that the Universe is expanding.
- 1931** Einstein stops using the **cosmological constant** to keep the Universe from expanding.
- 1931** Dirac shows that the existence of **magnetic monopoles** would lead to electric charge quantization.
- 1931 Georges De Rham** goes to work on his famous theorem in **cohomology** and characteristic classes -- results that would become very important in string theory.
- 1935** Young physicist **Subramanyan Chandrasekhar** is attacked by famous astronomer Arthur Eddington for his report that there is a stellar mass limit beyond which collapse to what we now call a **"black hole"** is inevitable. Chandrasekhar wins the Nobel Prize in 1983 for his work on stellar evolution.

- 1938 Wigner** constructs a class of irreducible unitary representations of the Lorentz group.
- 1939 Elements de Mathematique** by **Nicholas Bourbaki** (a pseudonym for a group of young mathematicians at the Ecole Normale in Paris) is begun. This extended set of works aims to set down in writing what is no longer in doubt but rather on a boring and rigorous footing in modern mathematics.
- 1943** Chinese mathematician **Shiing-Shen Chern** begins his work on characteristic classes and **fiber bundles** that will become an important tool for understanding quantum gauge theories and string theory.
- 1948 Richard Feynman, Julian Schwinger, and Tomonaga Shin'ichiro** report that the divergent integrals that plague the **quantum gauge field theory of electrodynamics (QED)** can be sensibly dealt with through the process of **renormalization**.
- 1953** Based on particle scattering data, **Murray Gell-Mann** suggests that there is a new quantum number called hypercharge (which we now call "**stangeness**") and recognize as a part of the quark model coming from the **strange quark**. Gell-Mann receives the Nobel Prize in 1969 for his work on the quark model.
- 1954 Gell-Mann and Francis Low** develop the idea that the physical content of a quantum theory should be invariant under a change of scale in the theory. This is called **renormalization group**. It turns out to constrain quantum field theories enough to make it a very powerful tool for analyzing asymptotic behavior of quantum theories.
- 1954 C.N. Yang and R. Mills** develop **non-Abelian gauge invariance** -- an idea that takes 17 years to gain acceptance before it revolutionizes particle physics.
- 1954 Eugenio Calabi** conjectures the existence of a Kähler manifold with a Ricci-flat metric with a vanishing first Chern class and a given complex structure and Kähler class. This funny-sounding stuff will eventually become of major importance in understanding *superstring* theory.
- 1964** Cambridge mathematician **Roger Penrose** proves that a black hole space-time must contain behind the black hole event horizon a '**singularity**' where space-time physics ceases to make good sense.
- 1964 Gell-Mann and George Zweig** independently propose fundamental particles that Gell-Mann succeeds in naming "**quarks**".
- 1964 Peter Higgs, Francois Englert, and R. Brout** suggest a method of breaking quantum gauge symmetry that is later called the Higgs mechanism (or "**Higgs particle**").
- 1967** In his paper "*A Model of Leptons*", **Steven Weinberg** relies on Lie group theory combined with quantum field theory to explain the weak nuclear and electromagnetic forces in a single theory using the Higgs mechanism to give mass to the weak bosons. **Adbus Salam** and **Sheldon Glashow** share the Nobel Prize with Weinberg in 1979 for **Electroweak Theory**.
- 1967 Sidney Coleman and Jeffrey Mandula** prove that well-behaved particle scattering theories can't have symmetry algebras that relate particles of different spin. But the strict consequences of the

Coleman-Mandula Theorem were avoided by the **supersymmetry algebras** that were discovered a few years later.

1968 Michael Atiyah and Isadore Singer begin their work on **The Index of Elliptic Operators**. They prove the Atiyah-Singer index theorem -- a powerful mathematical result that will later be used extensively in theoretical physics.

1968 Gabriele Veneziano begins modern string theory with his paper on the dual resonance model of the strong interactions.

1970 Yoichiro Nambu, Leonard Susskind, and Holger Nielsen independently discover that the dual resonance model devised by Veneziano is based on the quantum mechanics of "**relativistic vibrating strings**". String theory begins.

1971 Gerard 't Hooft publishes his proof that the **electroweak gauge theory** of Weinberg is renormalizable and a new chapter in theoretical physics begins -- **the age of Quantum Gauge Field theory**.

1971 Pierre Ramond, André Neveu, and John Schwarz develop a string theory with fermions and bosons. Gervais and Sakita show that this theory obeys what turns out to be a **supersymmetry algebra** in 2 dimensions.

1971 Ken Wilson publishes work using the renormalization group to understand the quantum behavior of systems undergoing phase transitions. This opens up the study of critical phenomena in particle physics and leads to greater understanding of quark confinement. Wilson wins the Nobel Prize in 1981.

1971 Soviet physicists **Yuri Gol'fand** and **E. Likhtman** extend the *Poincaré algebra* into a superalgebra and discover supersymmetry in 4 space-time dimensions.

1973 David Gross, David Politzer, Frank Wilczek, and Gerard 't Hooft arrive at the conclusion that the coupling constant in non-Abelian quantum gauge theories vanishes at high energy. This is called *asymptotic freedom* and is one of the major results in the history of Quantum Gauge Field theory.

1973 Quantum Field Theories with space-time supersymmetry in 4 space-time dimensions are discovered by **Julius Wess** and **Bruno Zumino**.

1974 Stephen Hawking combines Quantum Field Theory with classical General Relativity and predicts that **black holes** radiate through particle emission, behave as thermodynamic objects, and decay with a finite lifetime into objects that we don't yet understand.

1974 Magnetic monopole solutions of non-Abelian gauge field theories are found separately by **'t Hooft** and Moscow physicist **Alexander Polyakov**.

1974 Joel Scherk and John Schwarz propose **string theory** as a theory of quantum gravity -- an idea that takes 10 years to be widely appreciated.

1974 Howard Georgi and Sheldon Glashow propose SU(5) for a "**Grand Unified Theory**" (GUT) of all forces except gravity. The theory also predicts that protons could decay.

- 1975** *Instanton* solutions of Yang-Mills equations are discovered by **Belavin, Polyakov, A. Schwarz,** and **Tyupkin**. This is exciting because "instantons" can tell us about non-perturbative physics that is not approachable by other means of calculation.
- 1976** **Shing-Tung Yau** proves the Calabi conjecture and discovers the *Calabi-Yau space* -- an important development for later progress in string theory.
- 1980** **Alan Guth** puts forward the idea of an **Inflationary** phase of the early Universe before the Big Bang.
- 1981** **Michael Green** and **John Schwarz** develop *superstring theory*.
- 1981** After Schoen and Yau do it in a more traditional manner, **Ed Witten** uses supersymmetry to prove the positive mass conjecture.
- 1982** Mathematician **Karen Uhlenbeck** shows that Yang-Mills instantons discovered by physicists can be used as a powerful analytical tool in abstract mathematics.
- 1983** **Witten** and **Luis Alvarez-Gaumé** derive general formulas for gauge and gravitational anomalies in quantum field theories in any dimension. They show that the gravitational anomalies cancel in Type IIB superstring theory.
- 1983** Mathematics graduate student **Simon Donaldson** discovers *exotic 4-manifolds* using instanton techniques learned in part from Uhlenbeck.
- 1984** **Michael Green** and **John Schwarz** show that superstring theory is free from quantum anomalies if the **spacetime dimension is 10** and the quantum gauge symmetry is $SO(32)$ [or E_8 times E_8].
- 1984** **Gross, Harvey, Martinec,** and **Rohm** find another class of anomaly-free superstring theories and call it the *heterotic string theory*.
- 1985** **Candelas, Strominger, Horowitz,** and **Witten** propose the use of *Calabi-Yau spaces* for the **extra 6 dimensions** in heterotic string theory.
- 1991** **Connes** and **Lott** develop **non-commutative geometry** which will find its way into the heart of string theorists at the turn of the millennium.
- 1993** In search of an understanding of black hole entropy, **'t Hooft** suggests the idea that the information in a 3+1-dimensional system cannot be greater than what is need to store it as an image in 2+1 dimensions. **Susskind** generalizes this idea and applies it to string theory in his paper [*The World as a Hologram*](#) and the "**Holographic Principle**" is born.
- 1994** [**Nathan Seiberg and Ed Witten**](#) discover **electric-magnetic duality** in $N=2$ supersymmetric gauge theory in 4 space-time dimensions, with very important applications in both mathematics and string theory.
- 1995** [**Witten**](#) and [**Townsend**](#) introduce the idea of Type IIA superstring theory as a special limit of **11-dimensional supergravity theory** with quantized membranes. This begins the **M-theory** revolution in superstring theory and leads people to ponder the role of space-time in string theory.

- 1995 **Andrew Wiles** -- with help from Richard Taylor -- completes a rigorous proof of *Fermat's Last Theorem*.
- 1995 **Joseph Polchinski** ignites the **D-brane revolution** in string theory with his paper describing extended objects in string theory formed by dual open strings with Dirichlet boundary conditions.
- 1996 In their paper *[Microscopic Origin of Black Hole Entropy](#)*, **Andy Strominger** and **Cumrun Vafa** use D-branes to count the quantum states of an extreme black hole and their result matches the Bekenstein-Hawking value. This stimulates new respect for string theory from the relativity community.
- 1997 **Juan Maldacena** finds that string theory in a background of 5-dimensional anti-de Sitter space times a 5-sphere obeys a duality relationship with *superconformal field theory* in 4 space-time dimensions. The result -- called **AdS-CFT duality** -- opens up a new era of exploration in string theory.

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