

Nobel Laureate Lecture

The Coming Revolutions In Fundamental Physics



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L.01 Room, Lecture Building

The Faculty of Science,

Mahidol University

Prof. David J. Gross

2004 Nobel Laureate for Physics

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"The coming revolutions in fundamental physics"

by

Prof. David J. Gross

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Abstract

Prof. Gross reviews the present state of knowledge in elementary particle physics and the questions that we are currently addressing. He discusses the experimental revolutions that might occur at the Large Hadron Collider, soon to be finished at CERN. He also reviews the state of string theory. The necessity to go beyond the standard model of particle physics and to understand quantum gravity has led to this ambitious attempt to unify all the forces of nature and all forms of matter as different vibrations of a string-like object. But string theory is still in a pre-revolutionary stage. Although remarkable progress has been achieved in the last decade in understanding the perturbative and non-perturbative structure of string theory, we still lack a fundamental understanding of the theory. Many string theorists suspect that a profound conceptual change in our concept of space and time will be required for the final formulation of string theory.

Biography

Prof. David Jonathan Gross



Prof. David Jonathan Gross is a 2004 Nobel Laureate for Physics and the director and holder of the Frederick W. Gluck Chair in Theoretical Physics at the Kavli Institute for Theoretical Physics of the University of California in Santa Barbara.

Born in Washington, D.C., David J. Gross received his undergraduate degree from Hebrew University in Jerusalem in 1962 and then returned to the United States to continue his education at the University of California, Berkeley, from where he received his Ph.D. in physics in 1966. He left Berkeley later that year to serve as a junior fellow at Harvard University.

David J. Gross began his professional teaching career at Princeton University in 1969 and was appointed professor of physics in 1972. During that same period, between 1970 and 1975, he also became a fellow at the Sloan Foundation. David J. Gross remained at Princeton until 1996, where he was named Eugene Higgins Professor of Physics (1986-1995) and Thomas Jones Professor of Mathematical Physics (1995-1997). In 1997 he was appointed director of the Institute of Theoretical Physics at the University of California, Santa Barbara, a position he holds until this day.

Professor Gross has also been a Fellow of the American Physical Society, the American Academy of Arts and Sciences and the American Association for the Advancement of Science and a Member of the National Academy of Sciences. He is the recipient of the J. J. Sakurai Prize of the American Physical Society, a MacArthur Foundation Fellowship, the Dirac Medal, the Oscar Klein Medal and the Harvey Prize of the Technion. He has received various honorary degrees and was selected to receive France's highest scientific honor, the Grande Médaille D'Or, for his contributions to the understanding of fundamental physical reality.

In 2004 David J. Gross, together with **H. David Politzer** and **Frank Wilczek**, was awarded the Nobel Prize for Physics for discoveries regarding the strong force—the nuclear force that binds together quarks (the smallest building blocks of matter) and holds together the nucleus of the atom.

The prizewinning work of David J. Gross and of his first graduate student Frank Wilczek—with H. David Politzer working independently—arose from physics experiments with particle accelerators conducted in the early 1970s to study quarks and the force that acts on them. During their research the three scientists observed that quarks were so tightly bound together that they could not be separated as individual particles but that the closer quarks approached one another, the weaker the strong force became. When quarks were brought very close together, the force was so weak that the quarks acted almost as if they were free particles not bound together by any force. When the distance between two quarks increased, however, the force became greater—an effect analogous to the stretching of a rubber band. This phenomenon became known as asymptotic freedom, and it led to a completely new physical theory, quantum chromodynamics (QCD), to describe the strong force.

This theory was an important contribution to the Standard Model, the theory that describes all physics connected with the electromagnetic force (which acts between charged particles), the weak force (which is important for the sun's energy production) and the strong force (which acts between quarks). With the aid of QCD physicists can at last explain why quarks only behave as free particles at extremely high energies. In the proton and the neutron they always occur in triplets. QCD has been widely accepted to be the best understanding of how the universe works and has brought physics one step closer to fulfilling a grand dream: to formulate a unified theory comprising gravity as well as a theory for everything.

More recently, Professor Gross has been engaged in research in superstring theory being the co-inventor of a new **superstring model**.

Source:

Gross, David J. (2007). In *Encyclopædia Britannica*. Retrieved December 30, 2007, from Encyclopædia Britannica Online: <http://www.britannica.com/eb/article-9400251>

String theory

in particle physics, a theory that attempts to merge quantum mechanics with Albert Einstein's general theory of relativity. The name string theory comes from the modeling of subatomic particles as tiny one-dimensional “stringlike” entities rather than the more conventional approach in which they are modeled as zero-dimensional point particles. The theory envisions that a string undergoing a particular mode of vibration corresponds to a particle with definite properties such as mass and charge. In the 1980s, physicists realized that string theory had the potential to incorporate all four of nature's forces—gravity, electromagnetism, strong force, and weak force—and all types of matter in a single quantum mechanical framework, suggesting that it might be the long-sought unified field theory. While string theory is still a vibrant area of research that is undergoing rapid development, it remains a purely mathematical construct because it has yet to make contact with experimental observations.

Relativity and quantum mechanics

In 1905 Einstein unified space and time with his special theory of relativity, showing that motion through space affects the passage of time. In 1915 Einstein further unified space, time, and gravitation with his general theory of relativity, showing that warps and curves in space and time are responsible for the force of gravity. These were monumental achievements, but Einstein dreamed of an even grander unification. He envisioned one powerful framework that would account for space, time, and all of nature's forces—something he called a unified theory. For the last three decades of his life, Einstein relentlessly pursued his quixotic vision. Although from time to time rumours spread that he had succeeded, closer scrutiny always dashed such hopes. Most of Einstein's contemporaries considered the search for a unified theory to be a hopeless, if not misguided, quest.

In contrast, the primary concern of theoretical physicists from the 1920s onward was quantum mechanics—the emerging framework for describing atomic and subatomic processes. Particles at these scales have such tiny masses that gravity is essentially irrelevant in their interactions, and so for decades quantum mechanical calculations generally ignored relativistic effects. Instead, by the late 1960s the focus was on a different force—the strong force, which binds together the protons and neutrons within atomic nuclei. Gabriele Veneziano, a young theorist working at the European Organization for Nuclear Research (CERN), contributed a key breakthrough in 1968 with his realization that a 200-year-old formula, the Euler beta function, was capable of explaining much of the data on the strong force then being collected at various particle accelerators around the world. A few years later, three physicists—Leonard Susskind of Stanford University, Holger Nielsen of the Niels Bohr Institute, and Yoichiro Nambu of the University of Chicago—significantly amplified Veneziano's insight by showing that the mathematics underlying his proposal described the vibrational motion of minuscule filaments of energy that resemble tiny strands of string, inspiring the name string theory. Roughly speaking, the theory suggested that the strong force amounted to strings tethering together particles attached to the strings' endpoints.

Strong force:

a fundamental interaction of nature that acts between subatomic particles of matter. The strong force binds quarks together in clusters to make more-familiar subatomic particles, such as protons and neutrons. It also holds together the atomic nucleus and underlies interactions between all particles containing quarks.

The strong force originates in a property known as colour. This property, which has no connection with colour in the visual sense of the word, is somewhat analogous to electric charge. Just as electric charge is the source of electromagnetism, or the electromagnetic force, so colour is the source of the strong force. Particles without colour, such as electrons and other leptons, do not “feel” the strong force; particles with colour, principally the quarks, do “feel” the strong force. Quantum chromodynamics, the quantum field theory describing strong interactions, takes its name from this central property of colour.

Protons and neutrons are examples of baryons, a class of particles that contain three quarks, each with one of three possible values of colour (red, blue, and green). Quarks may also combine with antiquarks (their antiparticles, which have opposite colour) to form mesons, such as pi mesons and K mesons. Baryons and mesons all have a net colour of zero, and it seems that the strong force allows only combinations with zero colour to exist. Attempts to knock out individual quarks, in high-energy particle collisions, for example, result only in the creation of new “colourless” particles, mainly mesons.

In strong interactions the quarks exchange gluons, the carriers of the strong force. Gluons, like photons (the messenger particles of the electromagnetic force), are massless particles with a whole unit of intrinsic spin. However, unlike photons, which are not electrically charged and therefore do not feel the electromagnetic force, gluons carry colour, which means that they do feel the strong force and can interact among themselves. One result of this difference is that, within its short range (about 10^{-15} metre, roughly the diameter of a proton or a neutron), the strong force appears to become stronger with distance, unlike the other forces.

As the distance between two quarks increases, the force between them increases rather as the tension does in a piece of elastic as its two ends are pulled apart. Eventually the elastic will break, yielding two pieces. Something similar happens with quarks, for with sufficient energy it is not one quark but a quark-antiquark pair that is “pulled” from a cluster. Thus, quarks appear always to be locked inside the observable mesons and baryons, a phenomenon known as confinement. At distances comparable to the diameter of a proton, the strong interaction between quarks is about 100 times greater than the electromagnetic interaction. At smaller distances, however, the strong force between quarks becomes weaker, and the quarks begin to behave like independent particles, an effect known as asymptotic freedom.

Quark:

any member of a group of elementary subatomic particles that interact by means of the strong force and are believed to be among the fundamental constituents of matter. Quarks associate with one another via the strong force to make up protons and neutrons, in much the same way that the latter particles combine in various proportions to make up atomic nuclei. There are six types, or flavours,

of quarks that differ from one another in their mass and charge characteristics. These six quark flavours can be grouped in three pairs: up and down, charm and strange, and top and bottom. Quarks appear to be true elementary particles; that is, they have no apparent structure and cannot be resolved into something smaller. In addition, however, quarks always seem to occur in combination with other quarks or with antiquarks, their antiparticles, to form all hadrons—the so-called strongly interacting particles that encompass both baryons and mesons.

Throughout the 1960s theoretical physicists, trying to account for the ever-growing number of subatomic particles observed in experiments, considered the possibility that protons and neutrons were composed of smaller units of matter. In 1961 two physicists, Murray Gell-Mann of the United States and Yuval Ne'eman of Israel, proposed a particle classification scheme called the Eightfold Way, based on the mathematical symmetry group SU(3), which described strongly interacting particles in terms of building blocks. In 1964 Gell-Mann introduced the concept of quarks as a physical basis for the scheme, having adopted the fanciful term from a passage in James Joyce's novel *Finnegans Wake*. (The American physicist George Zweig developed a similar theory independently that same year and called his fundamental particles “aces.”) Gell-Mann's model provided a simple picture in which all mesons are shown as consisting of a quark and an antiquark and all baryons as composed of three quarks. It postulated the existence of three types of quarks, distinguished by unique “flavours.” These three quark types are now commonly designated as “up” (u), “down” (d), and “strange” (s). Each carries a fractional value of the electron charge (i.e., a charge less than that of the electron, e). The up quark (charge $\frac{2}{3}e$) and down quark (charge $-\frac{1}{3}e$) make up protons and neutrons and are thus the ones observed in ordinary matter. Strange quarks (charge $-\frac{1}{3}e$) occur as components of K mesons and various other extremely short-lived subatomic particles that were first observed in cosmic rays but that play no part in ordinary matter.

The interpretation of quarks as actual physical entities initially posed two major problems. First, quarks had to have half-integer spin (intrinsic angular momentum) values for the model to work, but at the same time they seemed to violate the Pauli exclusion principle, which governs the behaviour of all particles (called fermions) having odd half-integer spin. In many of the baryon configurations constructed of quarks, sometimes two or even three identical quarks had to be set in the same quantum state—an arrangement prohibited by the exclusion principle. Second, quarks appeared to defy being freed from the particles they made up. Although the forces binding quarks were strong, it seemed improbable that they were powerful enough to withstand bombardment by high-energy particle beams from accelerators.

These problems were resolved by the introduction of the concept of colour, as formulated in quantum chromodynamics (QCD). In this theory of strong interactions, whose breakthrough ideas were published in 1973, colour has nothing to do with the colours of the everyday world but rather represents a property of quarks that is the source of the strong force. The colours red, green, and blue are ascribed to quarks, and their opposites, antired, antigreen, and antiblue, are ascribed to antiquarks. According to QCD, all combinations of quarks must contain mixtures of these imaginary colours that cancel out one another, with the resulting particle having no net colour. A baryon, for example, always consists of a combination of one red, one green, and one blue quark and so never violates the exclusion principle. The property of colour in the strong force plays a role analogous to that of electric charge in the electromagnetic force, and just as charge implies the exchange of photons between charged particles, so does colour involve the exchange of massless particles called gluons among quarks. Just as photons carry electromagnetic force, gluons transmit

the forces that bind quarks together. Quarks change their colour as they emit and absorb gluons, and the exchange of gluons maintains proper quark colour distribution.

The binding forces carried by the gluons tend to be weak when quarks are close together. Within a proton (or other hadron), at distances of less than 10^{-15} metre, quarks behave as though they were nearly free. This condition is called asymptotic freedom. When one begins to draw the quarks apart, however, as when attempting to knock them out of a proton, the effect of the force grows stronger. This is because, as explained by QCD, gluons have the ability to create other gluons as they move between quarks. Thus, if a quark starts to speed away from its companions after being struck by an accelerated particle, the gluons utilize energy that they draw from the quark's motion to produce more gluons. The larger the number of gluons exchanged among quarks, the stronger the effective binding forces become. Supplying additional energy to extract the quark only results in the conversion of that energy into new quarks and antiquarks with which the first quark combines. This phenomenon is observed at high-energy particle accelerators in the production of “jets” of new particles that can be associated with a single quark.

The discovery in the 1970s of the “charm” (*c*) and “bottom” (*b*) quarks and their associated antiquarks, achieved through the creation of mesons, strongly suggests that quarks occur in pairs. This speculation led to efforts to find a sixth type of quark called “top” (*t*), after its proposed flavour. According to theory, the top quark carries a charge of $\frac{2}{3}e$; its partner, the bottom quark, has a charge of $-\frac{1}{3}e$. In 1995 two independent groups of scientists at the Fermi National Accelerator Laboratory reported that they had found the top quark. Their results give the top quark a mass of 173.8 ± 5.2 gigaelectron volts (GeV; 10^9 eV). (The next heaviest quark, the bottom, has a mass of about 4.2 GeV.) It has yet to be explained why the top quark is so much more massive than the other elementary particles, but its existence completes the Standard Model, the prevailing theoretical scheme of nature's fundamental building blocks.

Asymptotic freedom (physics):

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characteristic of quarks (in subatomic particle: Asymptotic freedom) ...each contributing to the net force. When the quarks are close together, they exchange fewer gluons, and the force is weaker. Only at infinitely close distances are quarks free, an effect known as asymptotic freedom. For their discovery of this effect, Gross, Wilczek, and Politzer were awarded the 2004 Nobel Prize for Physics.

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Quantum chromodynamics (QCD)

in physics, the theory that describes the action of the strong force. QCD was constructed in analogy to quantum electrodynamics (QED), the quantum field theory of the electromagnetic force. In QED the electromagnetic interactions of charged particles are described through the emission and subsequent absorption of massless photons, best known as the “particles” of light; such interactions are not possible between uncharged, electrically neutral particles. The photon is described in QED as the “force-carrier” particle that mediates or transmits the electromagnetic force. By analogy with QED, quantum chromodynamics predicts the existence of force-carrier particles called gluons, which transmit the strong force between particles of matter that carry “colour,” a form of strong “charge.” The strong force is therefore limited in its effect to the behaviour of elementary subatomic particles called quarks and of composite particles built from quarks—such as the familiar protons and neutrons that make up atomic nuclei, as well as more-exotic unstable particles called mesons.

In 1973 the concept of colour as the source of a “strong field” was developed into the theory of QCD by European physicists Harald Fritzsch and Heinrich Leutwyler, together with American physicist Murray Gell-Mann. In particular, they employed the general field theory developed in the 1950s by Chen Ning Yang and Robert Mills, in which the carrier particles of a force can themselves radiate further carrier particles. (This is different from QED, where the photons that carry the electromagnetic force do not radiate further photons.)

In QED there is only one type of electric charge, which can be positive or negative—in effect, this corresponds to charge and anticharge. To explain the behaviour of quarks in QCD, by contrast, there need to be three different types of colour charge, each of which can occur as colour or

anticolour. The three types of charge are called red, green, and blue in analogy to the primary colours of light, although there is no connection whatsoever with colour in the usual sense.

Colour-neutral particles occur in one of two ways. In baryons—subatomic particles built from three quarks, as, for example, protons and neutrons—the three quarks are each of a different colour, and a mixture of the three colours produces a particle that is neutral. Mesons, on the other hand, are built from pairs of quarks and antiquarks, their antimatter counterparts, and in these the anticolour of the antiquark neutralizes the colour of the quark, much as positive and negative electric charges cancel each other to produce an electrically neutral object.

Quarks interact via the strong force by exchanging particles called gluons. In contrast to QED, where the photons exchanged are electrically neutral, the gluons of QCD also carry colour charges. To allow all the possible interactions between the three colours of quarks, there must be eight gluons, each of which generally carries a mixture of a colour and an anticolour of a different kind.

Because gluons carry colour, they can interact among themselves, and this makes the behaviour of the strong force subtly different from the electromagnetic force. QED describes a force that can extend across infinite reaches of space, although the force becomes weaker as the distance between two charges increases (obeying an inverse square law). In QCD, however, the interactions between gluons emitted by colour charges prevent those charges from being pulled apart. Instead, if sufficient energy is invested in the attempt to knock a quark out of a proton, for example, the result is the creation of a quark-antiquark pair—in other words, a meson. This aspect of QCD embodies the observed short-range nature of the strong force, which is limited to a distance of about 10^{-15} metre, shorter than the diameter of an atomic nucleus. It also explains the apparent confinement of quarks—that is, they have been observed only in bound composite states in baryons (such as protons and neutrons) and mesons.