Nobel for a Minus Sign

The 2004 Nobel Prize in Physics

Rohini M Godbole and Sunil Mukhi

In this article we survey the research work for which the Nobel Prize in Physics was awarded in 2004, and discuss the three scientists – David Gross, H David Politzer and Frank Wilczek, who received the honour.

Introduction

In an article in *Resonance* on the Nobel Prize in Physics for the year 1999, one of us [1] wrote "The only part of this edifice (of the Standard Model of particle physics) that is not yet honoured with a Nobel Prize is QCD or Quantum Chromodynamics: the gauge theory of strong interactions. Who knows, in a few years we may be reading about the work of D Gross, H D Politzer and F Wilczek in a similar article!" And indeed, the Nobel Prize in Physics for the year 2004 has been awarded to these three scientists for their 1973 "discovery of asymptotic freedom in the theory of the strong interaction" This discovery was essential for particle physicists to arrive at a consistent mathematical description of the fundamental constituents of matter called quarks, and the interactions between them.

The Nobel Academy's announcement concludes with the observation: "Thanks to their discovery, David Gross, David Politzer and Frank Wilczek have brought physics one step closer to fulfilling a grand dream, to formulate a unified theory comprising gravity as well – a theory for everything." This discovery truly played a unifying role: it convinced particle physicists that the mathematical framework for the description of *all* fundamental constituents of matter and *all* interactions among them, is

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Keywords
Particle physics, quarks, strong interactions, quantum chromodynamics, asymptotic freedom.

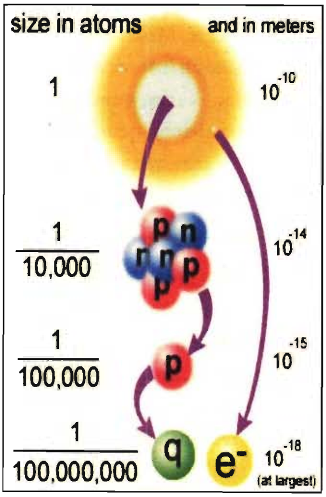
the same. At least, this is true if we ignore the gravitational interaction, about which the present discovery had nothing to say and with which the remaining obstacles to unification are associated.

This Nobel Prize has been anticipated by the entire particle physics community for several years now. In this article, we will try to place the prize in context, by describing the area of physics pertinent to the prize-winning work, the questions which the winners tried to address, and the work they actually did. In particular, we will try to explain in simple terms what is meant by 'asymptotic freedom' – the keyword associated to this work. We will also talk about the scientists who achieved this remarkable recognition.

Standard Model of Particle Physics: Bricks and Mortar

Particle Physics is the study of the fundamental constituents of matter and the interactions among them. These can be thought of as the building blocks of matter and the mortar that glues them together [1,2]. Not only the building blocks, but also the mortar corresponds to elementary particles, the latter being known as force carriers. *Figure* 1 shows the constituents of matter at different distance scales, beginning with atoms whose size is 10^{-10} metres and ending with *quarks* and *leptons* which are a hundred million times smaller than an atom and are today believed to be indivisible. Hence we consider these to be the fundamental constituents of matter. Experiments at high energy accelerators, and the development of theoretical models, have together helped us arrive at this conclusion.

Figure 1. Constituents of matter at different distance scales.



Constituents, Forces and their Carriers: The quarks and leptons come in several different varieties, summarised in *Table* 1. Later we will get a glimpse of why so many varieties must be present. As for the force carriers, we know today that they are of four types, cor-

Table 1. The fundamental constituents of matter.

Quarks	Leptons
$\begin{pmatrix}u\\d\end{pmatrix}\ \begin{pmatrix}c\\s\end{pmatrix}\ \begin{pmatrix}t\\b\end{pmatrix}$ × 3 colors	$\begin{pmatrix}e^-\\\nu_e\end{pmatrix}\ \begin{pmatrix}\mu^-\\\nu_\mu\end{pmatrix}\ \begin{pmatrix}\tau^-\\\nu_\tau\end{pmatrix}$
i.e. $\begin{pmatrix}u\\d\end{pmatrix}\ \begin{pmatrix}u\\d\end{pmatrix}\ \begin{pmatrix}u\\d\end{pmatrix}$ and so on	'colourless Leptons'
+antiquarks	+ antileptons

responding to the four basic forces experienced by the constituents of matter:

1) Gravitational Force: The force that holds us on the earth, and gives rise to planetary motion as well as tides.

2) Electromagnetic Force: The force that hold electrons inside atoms, and that is responsible for electrostatic effects, electric currents, and magnetic poles.

3) Weak Force: The force that causes the β decay of radioactive nuclei.

4) Strong Force: The force that binds together the quarks inside protons and neutrons, and also makes the latter stick to each other to form the atomic nucleus.

The force responsible for holding the nucleons (protons and neutrons) together in a nucleus, is derived from the Strong Force above in a similar way that the 'Van der Waals' force between neutral atoms is derived from the Coulomb interaction among the charged constituents.

These forces are familiar to us to varying degrees, depending on their effects on the kind of objects that we encounter in daily life. For this reason, the first two forces in the above list have been known almost since the dawn of scientific thought, while the last two are

All quarks and antiquarks appear in three 'colours'. This abstract property of colour has nothing to do with real colours, so we could have called it by any other name of our choice such as 'taste' or 'smell'.

Interaction	Description	Carrier Particle
Gravitation	Long-range but extremely weak attraction between all particles.	Graviton
Electromagnetic	Long-range interaction of a quark or lepton with another quark or lepton	Photon γ
Weak	Short-range interaction that can cause different quarks and leptons to change into one another	*W/Z* Bosons
Strong	Short-range interaction among quarks only	Gluons g

Table 2. Four basic forces in Nature, and their four carriers.

nuclear forces and were discovered only in the twentieth century. The effects of the latter two forces cannot be observed directly by the human senses, but they are just as real as the first two, since experimental equipment is certainly able to detect them.

As we mentioned above, these forces are conveyed between the constituents of matter via the mediation of other particles called force carriers. These are listed and briefly described in *Table* 2. *Figure* 2 has the same information illustrated in pictures.

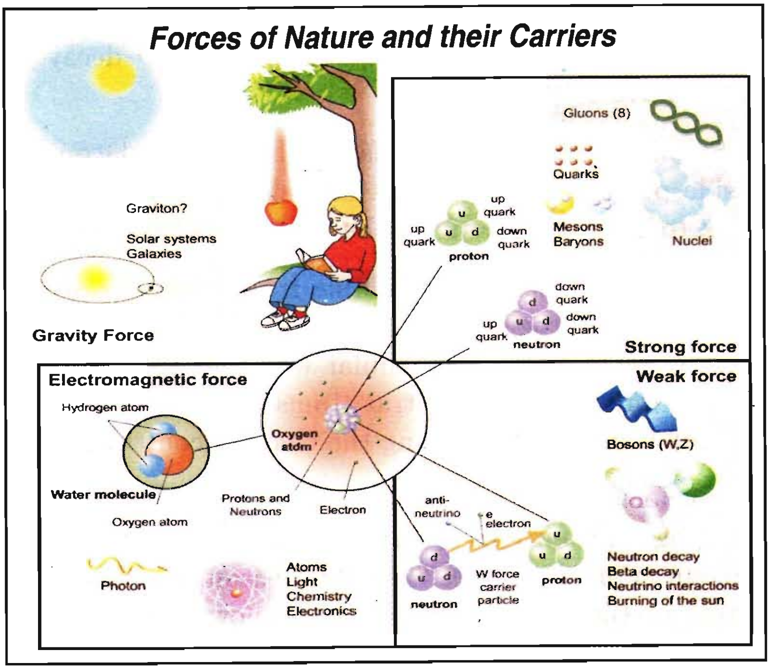


Figure 2. A pictorial presentation of the four forces and their carriers.

Fermions and Bosons: Let us recall here that most elementary particles carry a 'spin', or intrinsic angular momentum. We believe this because of experiments in which particles seem to be spinning on their own axis. This is not literally true: if it were, one should be able to change their amount of spin, or stop them from spinning, while in fact their spin angular momentum is an unchangeable property. So we must treat it as an intrinsic property of the particle. It turns out that it has to be always an integer or half-integer multiple of a basic unit called $\hbar$ or Planck's constant. This multiple is called the 'spin' of the particle. Particles of integer spin are called 'bosons' and those of half-integer spin, 'fermions'.

The effects of the nuclear forces cannot be observed directly by the human senses, but they are just as real as the more familiar forces of electricity and magnetism, since experimental equipment is certainly able to detect them.

Now in terms of their spin, there is an important difference between the constituents of matter (leptons and quarks) on the one hand, and the force carriers on the other. The constituents have half-integral spin, in fact they have precisely $\frac{1}{2}$ unit of spin. So they are all fermions. On the other hand, the carriers of the the electromagnetic, weak and strong forces (the photon γ, the W/Z bosons and the gluons g respectively), all carry one unit of spin and are therefore bosons.

Forces mediated by spin-1 particles are called 'gauge forces' The graviton, that mediates the gravitational interaction, carries two units of spin and this is at the root of the differences between gravity and all other interactions. But our focus here will be on the gauge particles. Indeed the story of this year's Nobel Prize is the story of one of these gauge forces: the strong force. As mentioned above, this acts between quarks through the mediation of gluons.

We will see that this force can be interpreted in terms of an abstract property called 'colour' (which has nothing to do with real colours, so we could have called it by any other name of our choice such as 'taste' or 'smell'). The 'colour' associated with the strong force is very much like

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the electric charge associated with the electromagnetic force. The main difference is that there are only two varieties of electric charge: positive and negative, while there are three varieties of colour (sometimes called red, green and blue) as well as their opposite 'anti-colours'. In order to be able to exchange these colour varieties, it also turns out that there must be precisely eight types of gluon.

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Leptons do not experience the strong force, which is their main distinguishing feature from quarks. Just as an electrically neutral or uncharged object feels no electromagnetic force, a colourless object will feel no strong force. In this interpretation, the leptons are therefore 'colourless'.

Standard Model as Gauge Theory: Can we be more precise when we talk of 'gauge forces' and 'colours'? These words actually refer to the mathematical formalism that describes all (or most) of particle physics. It is not enough to know what particles constitute matter and what particles mediate the forces between them. We seek much more quantitative information: what are the numerical values of the forces acting when we carry out a given experiment? Can our theory *predict* the results of an experiment in which elementary particles interact? If so, to what accuracy can it make a prediction?

As a result of over fifty years of research (including the work rewarded by the current Nobel Prize) it has been established that there is a mathematical framework that does exactly this job. It is called 'Quantum Field Theory'. There are a few different varieties of quantum field theory, one large class being 'Quantum Gauge Theory' [3] which describes interactions mediated by the gauge particles to which we have referred above. It is this class of theories that has been most successful in particle physics. A particular member of this class of theories, called the 'Standard Model' of particle physics, is

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consistent with all known properties of elementary particles and agrees amazingly well with all experiments performed on them so far.

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Nobel Prizes for the Standard Model: This situation arose as a result of a long historical development involving many stages. Almost every major stage has been rewarded with a Nobel Prize. It started in 1965 when Feynman, Schwinger and Tomonaga were awarded the Nobel Prize for their description of the electromagnetic interactions in terms of Quantum Electrodynamics (QED) – the first known example of a Quantum Field Theory. Despite being notoriously difficult and complicated, QED has turned out to be a relatively simple form of Quantum Gauge Theory!

In 1979, Glashow, Salam and Weinberg got a Nobel Prize for formulating a unified description of electromagnetic and weak interactions in terms of a Quantum Gauge Theory. This theory predicted the existence of unknown gauge particles, unknown at the time, the W and Z bosons as well as their masses. Van der Meer and Rubbia led a team that produced and discovered these bosons at a proton-antiproton accelerator called $Sp\bar{p}S$ at CERN[1] in Geneva. In 1984 they were rewarded with the Nobel Prize for this discovery.

When Glashow *et al* formulated their theory as a quantum gauge theory, they did not know for a fact that such theories exist! That may come as a surprise to a lay person. What does it mean for a theory not to exist? It is a remarkable and subtle fact that the theories describing elementary particles are full of potential inconsistencies. It is not enough to write down a general definition of the theory one wants to work with, though that is a necessary first step. After that, much hard work has to be done to show that such a theory really exists. This situation first surfaced with quantum electrodynamics. There it was possible to prove

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[1] CERN is the world's largest particle physics laboratory in Geneva, Switzerland and the acronym stands for 'European Organization for Nuclear Research'.

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consistency of the overall framework in a direct manner, though difficult. With the more general quantum gauge theories, many attempts had been made to show their consistency, but all had failed – until the problem was addressed by the Dutch physicists 'tHooft and Veltman. They proved consistency of quantum gauge theories in very general terms, and were awarded the Nobel Prize for this in 1999. Such a proof of consistency was not merely an assurance that the theory made sense, but also provided a practical tool to compute the properties of elementary particles to a high degree of accuracy.

The final Nobel Prize of interest to the present discussion is that awarded in 1990 to Friedman, Kendall and Taylor for performing experiments which revealed that a proton is made of a number of point-like constituents, called quarks or partons. However, at the time of their experiment it was not known what theory described these constituents and their interactions. That was a special challenge because, as we will see, quarks or partons exhibit very unusual behaviour that had not previously been encountered in particle physics. It was Gross, Wilczek and Politzer who put forward a proposal, based on quantum gauge theory, for a description of strong interactions. It has turned out to be spectacularly successful.

Until recently, this was the only crucial piece of the Standard Model which had not been rewarded with a Nobel Prize. In 2004, this situation was remedied and the Standard Model has received its due acknowledgement.

A Brief History of Quarks and Colour

Let us begin by recapitulating a bit of history of the quark idea. In the early 1960's, a large number of supposedly elementary particles had been discovered in cosmic-ray and bubble-chamber experiments. They exhibited regularities in their properties which led Gell-Mann and Zweig to propose that they were made up of a smaller number of more elementary particles, which they called 'quarks'.

This had a historical precedent. The energy levels of an atom can be seen in the form of atomic spectral lines, and its regularities lead us to believe that an atom consists of an electron moving in the central electrostatic potential of a nucleus. But in that case, the nucleus was directly seen in experiments and could even be broken up into free protons and neutrons. On the contrary, no one had ever broken up protons and neutrons into quarks. So people suspected that quarks were not 'real' entities, but some kind of mathematical abstraction. Worse, quarks were required to possess fractional electric charges (one-third or two-third the charge of an electron), something that should have been noticed if quarks could travel around by themselves. Hence many people regarded quarks as abstract entities, and the quark model as 'just mathematics'[2].

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According to the quark hypothesis, all the particles which experience strong interactions are made up of quarks: a proton is a bound state of two 'u-quarks' and one 'd-quark' and so on. The names u and d stand for 'up' and 'down' but just like colour, these are abstract concepts and could easily be given any other names. Indeed, the attribute of being 'up' or 'down' is called 'flavour'

To account for the particles then known, one required only three different flavours of quarks: u(p), d(own) and s(trange). A number of different high energy experiments gave results consistent with the quark hypothesis. With the advent of higher energies and the discovery of new particles, these three flavours proved insufficient for the quark hypothesis to work. So three more flavours were added: c(harm), b(eauty) and t(op).

Today we believe that there exist precisely these six flavours of quarks. Their presence is strongly, though indirectly, confirmed by experiments, and is also required

[2] The history of science is full of similar incidents. At one time, many chemists did not believe in the 'reality' of atoms, even while they successfully used the kinetic theory of gases in their work. As a matter of fact, the work on Brownian motion by Albert Einstein, almost exactly 100 years ago, was motivated by the desire to find a 'direct' proof for the existence of molecules.

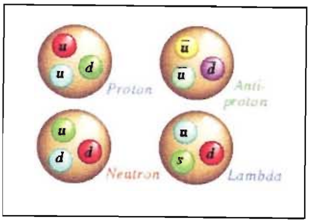

Figure 3. How quarks and antiquarks of different types make up the strongly interacting particles.

for consistency of the corresponding theory, the Standard Model. *Figure* 3 shows the composition of some of the known strongly interacting particles in terms of different quarks and (anti)quarks.

In 1965, soon after the original quark postulate, Greenberg, Han and Nambu proposed that each flavour of quark comes in three different species, differing only in an additional attribute which they called 'colour'. They were led to this hypothesis by formal considerations. Pauli's Exclusion Principle tells us that the wave function of a collection of identical fermions must be antisymmetric under the exchange of any two. Alternatively you may know this as a statement that no electrons with the same energy and spin can be in the same position. However, the existence of a particle called Δ^{++} posed a paradox for this principle. The paradox is straightforward to explain to a reader familiar with the basics of quantum mechanics, though the reader without this familiarity would have to accept it on faith. Briefly it goes as follows.

The electric charge of Δ^{++} is 2 in units of electron charge, and its spin is $\frac{3}{2}$ in units of $\hbar$. In terms of the quark model, Δ^{++} must consist of three u quarks. For it to have a spin $\frac{3}{2}$, the spins of the three identical quarks (each of spin $\frac{1}{2}$) have to be all aligned. Thus all the quarks would be able to occupy the same position with the same spin orientation. More technically, this says that the net wave function for Δ^{++} is *symmetric* under the exchange of any two u quarks. That would contradict the exclusion principle, a fundamental tenet of quantum mechanics. Thus the quark model, as understood at the time, had to be wrong, or incomplete.

To resolve the paradox, Greenberg, Han and Nambu were led to introduce an additional attribute, which they called 'colour', taking three different values (for example red, blue and green), solely so that the wave function could be made antisymmetric under an exchange of colour labels. In particular, the Δ^{++} would contain not three identical u quarks, but rather, one u quark of each colour. Then it would not be a problem to make the wave function antisymmetric and save the exclusion principle.

A large number of measurements, such as the rate of decay of a neutral pion into a pair of photons, gave evidence that the number of quark species is really three times what was previously thought, consistent with the colour hypothesis. However, at this time there was no evidence which would compel one to accept quarks, 'colourful' or otherwise, as genuine physical entities. All attempts to observe particles with fractional electromagnetic charges had failed. Thus, for a large class of physicists, the quark hypothesis was just a kind of 'mathematics' that explained very neatly a whole lot of observed properties but did not require quarks to actually exist.

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In the meanwhile, indirect evidence for both the quark hypothesis as well as the colour hypothesis was mounting, in different experiments such as muon-antimuon pair production in pion-proton collisions, or the production of strongly interacting particles in electron-positron collisions.

Experimental Evidence for Quarks

In the early twentieth century, Rutherford and his group had performed a famous experiment in which alpha particles were scattered off atoms, revealing the atom as a pointlike nucleus with electrons whirling around it and empty space in between. The key result was that the particles that struck the atom either went right through (because they passed through the empty space) or scattered right back (because they chanced to hit the very dense nucleus).

At around the time that the coloured quark model of the previous section was being developed, physicists at the Stanford Linear Accelerator (SLAC) were performing a proton analogue of this experiment. They smashed high energy electrons[3] against protons and measured the energy of the scattered electron, to extract information on the structure of the proton. These experiments yielded surprising results.

Scattering events can be classified as 'elastic' or 'inelastic' depending on whether the end products are the same as the initial ones or additional particles are produced. In the SLAC experiments it was found that the number of elastic events decreased very rapidly with increasing energy and angle of the scattered electron. But the number of inelastic events[4] did not decrease. Indeed, the cross-section depended only on the ratio of the final energy and the scattering angle, a phenomenon that was later called 'Bjorken scaling'. The significance of this scaling as emphasised by Bjorken and Feynman, is the following:

1) The electron was getting scattered from *charged, pointlike* constituents, which Feynman called 'partons', inside the proton.
2) The electron appeared to scatter independently from each of the partons, which could only happen if the partons had very weak interactions with each other. Thus the partons were approximately free.

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Further experimental tests, one of them suggested by David Gross with Curtis Callan at Princeton, revealed that the properties of these partons like electric charge and spin were the same as those required in the coloured quark model. This unified the formally motivated 'quark' and the experimentally detected 'parton' making it clear they were the same physical object. No longer could

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[3] These electrons were accelerated upto an energy of 25,000 Million Electron Volts (MeV).

[4] In these events the electron penetrated deep inside the proton, hence the process came to be known as 'Deep Inelastic Scattering' (DIS).

quarks be thought of as mathematical entities, since electrons were actually hitting them and bouncing off.

Asymptotic Freedom: A Paradox and Its Resolution

This, however, presented the world of particle physics with a new and very serious paradox. In the Rutherford experiment, the constituents of the 'hard' nucleus, the protons and neutrons, could be viewed in isolation outside the atom. So no doubts could remain about their existence. However, the quarks whose existence stood revealed in the Deep Inelastic Scattering (DIS) experiment, stubbornly refuse to emerge from inside the proton.

By itself this is not a paradox, for it could be explained by saying that the quarks are very tightly bound and huge energies are required to liberate them. However, this would be in sharp conflict with the results of the DIS experiment, according to which quarks inside the proton are 'free' of each other. How can quarks be non-interacting and yet so tightly bound as to be inseparable? The Nobel Prize winning work of David Gross, H David Politzer and Frank Wilczek provided a solution to this paradox, and in the process identified the mathematical structure of the theory of strong interactions.

Actually it is not hard to guess, with hindsight, what kind of interaction would leave the quarks free of each other when they are close by, but become strong as they are separated. Imagine an open rubber band with a marble attached at each end. If you leave the system on a table, the marbles will roll around largely independent of each other. So when the band is limp, the objects at the end appear not to interact with each other. On the other hand, once you stretch the band, the marbles discover that they are attached to each other. The force between them actually grows with distance! And if the band is unbreakable, one will never be able to isolate

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one marble from the other.

The electric charge of an electron is not really constant, as we naively assume. This is due to a phenomenon called screening.

So there was a physical picture of how quarks behave – the strong 'colour' force binds them as if they are attached by a rubber band. But in the framework of quantum field theory, what interaction could be found that led to this property? The most familiar field theory, quantum electrodynamics, does not behave this way. Between two charged particles, the electromagnetic interaction falls off with distance. That is why we can see free electrons separated from each other.

In quantum field theory, the vacuum, or state without any matter, is a seething, bubbling medium in which 'virtual' particles are constantly appearing and disappearing.

Now the electric charge of an electron is not really constant, as we naively assume. This is due to a phenomenon called screening. In quantum field theory, the vacuum, or state without any matter, is not as quiet as one might think. It is a seething, bubbling medium in which 'virtual' particles are constantly appearing and disappearing. This is a manifestation of the uncertainty in quantum theory. In this situation an isolated electron, having a negative charge, gets surrounded by a 'cloud' of positive charges that come out of the vacuum and are attracted to it. They tend to cancel off much of the electron's charge. This means that the actual electron charge is very large, but we observe only a small fraction of it when we are far away because the bulk of it is hidden by screening. As we approach the electron, we penetrate the screening charges and find a large amount of electric charge at the core. In fact, the effects of such a variation of charge with distance had to be included to explain the numerical value of the experimentally observed splitting between the $2P_{1/2}$ and $2S_{1/2}$ levels of hydrogen atom. So screening is not just a generic notion, but a tested fact.

One can calulate how the effective charge would vary with distance in quantum electrodynamics. The answer can be written, to a good approximation, as an equation

$$r\frac{de(r)}{dr} = -\beta(e(r))^3$$

where $e(r)$ is the effective charge observed at a distance r from the core of the particle, and β is a constant. It is clear that if β is positive, $e(r)$ will increase with decreasing distance (screening). But if β is negative, $e(r)$ will *decrease* with decreasing distance (anti-screening). In electrodynamics, β was found by calculation to be a positive number, consistent with the expected screening.

DIS suggests that the number β would have to be negative for a field theory of the strong interactions.

Now DIS suggests that in strong interactions, the effective charge *decreases* as particles come very close. How would one find such an interaction within quantum field theory? It would need to satisfy a very counter-intuitive 'anti-screening' property. Therefore the number β would have to be *negative.*

Until 1973, no quantum field theory had been known to give rise to anti-screening. But an important class of field theories was gaining prominence at the time: the non-Abelian gauge theories. Discovered in 1954 by Yang and Mills, this class of theories was a mathematical generalisation of Maxwell's electrodynamics which is an Abelian Gauge Theory [5](therefore people felt it was 'just mathematics'). One could introduce fermionic matter fields (quarks) in this theory, which would be organised into N-component objects for some whole number $N \geq 2$. This N was later to be identified with 'colour'

The interaction between them was mediated by a set of 'gauge fields' which are associated with the carrier gauge bosons we mentioned above, just like the electromagnetic field is associated with a photon. But the way these gauge bosons interacted with themselves in non-Abelian gauge theory was quite different from their counterpart in electrodynamics, the photon. In particular, unlike the photon, the non-Abelian gauge boson interacts with itself. Herein lies the heart of the story. This difference leads to a major change in the screening behaviour of the theory.

By 1973, it was known that gauge theories were consis-

[5] Refer to the article by Sourendu Gupta [3] for elaboration on these issues.

tent (recall that this is the work that got 't Hooft and Veltman the Nobel Prize in 1999). These theories had already proved useful in constructing the Glashow–Salam–Weinberg theory of electroweak interactions. But no one, at least in print, had asked whether these theories have the phenomenon of 'anti-screening'. Gross and Wilczek, and Politzer, showed that sometimes they do. In a calculation that ranks as a classic[6], they demonstrated that if there are N_f flavours of quarks and N colours, then β is *negative*, and the theory exhibits anti-screening, if $11N > 2N_f$. On the other hand, if $2N_f > 11N$ then β is positive and there is screening.

Now according to the quark hypothesis, $N = 3$, since we need precisely 3 colours. And experiments have confirmed that the flavours are precisely the ones that we have encountered: 'up, down, strange, charm, bottom, top', making 6 in all. We easily see that $11N = 33$ is greater than $2N_f = 12$. Thus this particular gauge theory has *negative* β and hence anti-screening. The effective colour charge of a quark *decreases* as we go closer to it. This property is called 'asymptotic freedom' Measurements of the colour charge of quarks at accelerators have now confirmed that they indeed exhibit this behaviour.

This calculation explains why quarks inside the nucleon behave as if they are nearly free, and therefore why the parton model and Bjorken scaling work. In fact, a more careful analysis shows that the theory predicts precise violations of Bjorken scaling that would be seen at very high momentum transfers, and this was also verified experimentally.

The effective colour charge of a quark *decreases* as we go closer to it. This property is called 'asymptotic freedom'.

But some puzzles remained open: Why are the quarks *never* liberated from the nucleon? And why don't we observe the new gauge bosons ('gluons') that were postulated to mediate the strong interactions? It took a little while to arrive at the right answer, simple as it seems

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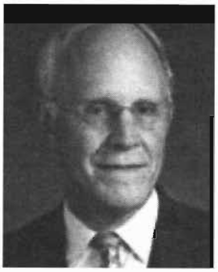
[6] Today, it is taught early on to any PhD student in particle physics.

Box 1. The Physicists

At the time the prize-winning work was done, David Gross was a junior faculty member at Princeton University, Frank Wilczek was his Ph.D. student, and David Politzer was a Ph.D. student with Sidney Coleman at Harvard University. All three awardees were quite young. For Frank Wilczek, 21, and David Politzer, 23, it constituted their Ph.D. thesis. The oldest of the three, at 33, was David Gross. In Gross's own words, Wilczek 'was my first graduate student and I thought that, well, all graduate students are as good as Frank.'

Gross, born in 1941, received his undergraduate education in physics at the Hebrew University, Jerusalem, then in 1966 got his Ph.D. with Geoffrey Chew at the University of California, Berkeley, working on a theoretical formulation of strong interactions which did not involve Quantum Field Theory. He has always been a leader in the Particle Physics community, charting new paths mainly in the area of String Theory, which is the prime candidate to unify all fundamental interactions including gravity. He was a Professor at Princeton till 1997, and then became Director of the Institute for Theoretical Physics (now called the Kavli Institute) at Santa Barbara.



Gross is a renowned teacher, and the list of his Ph.D. students contains a Nobel Laureate (Frank Wilczek) as well as a Fields Medallist (Edward Witten)* About a decade ago, Gross co-authored an influential article with Gordon Kane and Edward Witten called "The State of Exploratory Theory Beyond the Standard Model". This article was motivated by a recent sociological problem, the growing rift between two halves of the Particle Physics community: the phenomenologists, motivated directly by experimental results, and the formal theorists (mainly string theorists) motivated by consistency and mathematical elegance. The authors argued that each of the two approaches had its own rationale and neither side could afford to ignore or attack the other** Incidentally, Gross started his prize-winning work with Wilczek in the belief that NO Quantum Field Theory could have the right properties to reproduce the scaling properties seen in Deep Inelastic Scattering. But their calculation ultimately proved him wrong!

Interviewer: So, do you have any good advice to young students today? How they can behave and study to get the Nobel Prize once?

David Gross: Well, the advice I tell students is to think about the big problems. I mean, work on anything you can work on where you can make progress. But always keep in mind the big problems. The ones that are truly important. And, watch carefully what Nature is trying to tell us.

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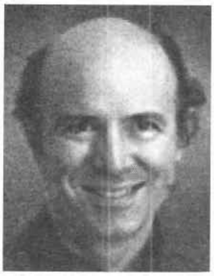
*The Fields Medal is the equivalent of a Nobel Prize in the field of Mathematics.

** The present article is authored by one member each from these two communities in India!

Box 1. continued...



As mentioned already, the other two prize winners, Politzer and Wilczek, were both doing this work as part of their Ph.D. thesis. The two have one more thing in common: both are New Yorkers. Wilczek born in Queens, where he went to high school, subsequently graduating from the University of Chicago. He then started as a graduate student in Mathematics at Princeton, but, as he says, taking Gross's Quantum Field Theory course showed him his true vocation and he has been a physicist since then. He has worked on a very broad range of topics, including applications of Field Theory to Condensed Matter Physics and the interface of Cosmology and Particle Physics. He was at Princeton University till 1981, then moved to UC Santa Barbara, then in 1988 to the Institute for Advanced Study, Princeton, and finally to the Masschussetts Institute of Technology in 2000.

David Politzer attended the famous Bronx High School of Science, which in 1966 had two future Nobel Laureates in their Science class (Russel Hulse, Nobel prizewinner for his discovery of Binary Pulsars, was Politzer's classmate). He graduated from the University of Michigan and then joined Harvard where he did his doctoral research with Sidney Coleman. He was motivated to undertake his calculations not so much by Bjorken Scaling, but rather by a desire to understand some aspects of Non Abelian Gauge Theories as applied to electroweak interactions. After his Ph.D. he moved to the California Institute of Technology where he is a faculty member to this day. He has worked predominantly in the theory of Strong Interactions, Quantum Chromodynamics, the very theory that he helped invent.

today. Steven Weinberg, who was to win a Nobel Prize for the Glashow–Salam–Weinberg theory, observed in a paper submitted shortly after those of Gross, Politzer and Wilczek that the opposite face of asymptotic freedom at short distances would be strong coupling at large distances – and this might lead to *permanent confinement* of both quarks and gluons. He called this phenomenon 'infrared slavery', because 'infrared' in quantum physics means 'long distance' – the opposite of 'asymptotic', which in this context means 'short distance' And of course, 'slavery' is the opposite of 'freedom'

Confinement had already been proposed by Nambu in 1970, but not in a gauge theory context. He had pursued the analogy of two quarks being connected by rubber bands. By thinking of the rubber band as a fundamental object, he had been led to the formulation of 'string

'string theory'[7]. Once it became clear that gauge theory can give rise to confinement (the evidence for this is utterly convincing, though even today, confinement in gauge theory has not yet been rigorously proved), the paradoxes were all resolved.

This Nobel prize-winning work started off the study of the field theory of interacting quarks and gluons, called Quantum Chromodynamics (QCD). QCD is now an integral part of the Standard Model of all particle interactions[8].

So one may ask, have all the discoveries regarding the Standard Model been rewarded with a Nobel Prize now? The answer is no. Two predictions still remain without direct experimental confirmation. One is the prediction of a new particle, the Higgs boson. Experiments which will start at the Large Hadron Collider (LHC) at CERN in 2007 are expected to detect this particle. The second feature of the Standard Model that still lacks direct evidence, concerns predictions of QCD when the distance between two quarks becomes large: exactly the opposite of the situation where Asymptotic Freedom holds. In this situation usual 'perturbative' methods of calculation fail. Alternate methods of studying field theories predict the formation of a state of coloured quarks and gluons called 'Quark Gluon Plasma' (QGP). This state can be formed for a period of about 10^{-23} seconds in collisions of heavy ions like lead or gold which are accelerated to relativistic speeds. Such experiments have started in the Brookhaven National Laboratory, USA. Both these experimental discoveries would surely rate a Nobel Prize. It is good news that Indian theorists and experimentalists are involved in research which has implications for both these experiments.

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[6] This remains a compelling physical picture of confinement, on which much research is focused today.

[8] We recall that here, 'all' really means 'all except gravity'.

Suggested Reading

[1] **Rohini M Godbole, *Resonance*, Vol.5, No.2, p.16, 2000.**

[2] **Ashoke Sen, *Resonance*, Vol.5, No.1, p.4, 2000.**

[3] **Sourendu Gupta, *Resonance*, Vol.6, No.2, p.29, 2001.**

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