spent by the cell. It therefore appears that a head on collision is more expensive for the cell than a co-directional collision.

Hence, the cells appear to have evolved a strategy by which these highly efficient copying machineries have some degree of flexibility in switching template strands. Since a co-directional collision between RNA and DNA polymerases is more energy efficient than a head-on collision, the genetic material of several prokaryotes such as bacteria and viruses is organised in a manner which ensures that most of the frequently transcribed genes are oriented in the direction of the replication fork movement. The clash between the "Titans" being inevitable, cells have to chosen the least harmful way to deal with it. The genetic material of eukaryotes is quite complex and its sheer size makes the understanding of such processes a daunting task. At this moment one can simply hypothesize that since the eukaryotic replication and transcription machineries share common structural organisations with their prokaryotic counterparts, what is good for *E.coli* may also hold good for an elephant!

Sanjeev Galande is a research scholar at the Department of Biochemistry, Indian Institute of Science, Bangalore.

Discovery of the Top Quark

Missing Member of the Family Traced

R Ramachandran

All matter in the universe is believed to be made up of quarks (which are subconstituents of protons, neutrons, mesons, etc.) and leptons (such as electrons and neutrinos). The dynamics of these quarks and leptons which lead to electromagnetic, weak radioactive and strong nuclear forces are governed by laws which are a generalized form of Maxwell's laws of electromagnetism.

Most matter exists as molecules and atoms. Atoms consist of compact nuclei containing protons and neutrons held together by nuclear forces, and negatively charged electrons which are bound electrically to these nuclei. High-energy scattering experiments enable us to see if protons and neutrons have a substructure. Indeed experiments involving high-energy inelastic scattering of electrons (or muons) reveal that nucleons (protons and neutrons) are bound states of two species of quarks, generally referred

> **Our universe consists mostly of the 'up' and 'down' quarks and the electron and electron neutrino.**

By the 1970's it became clear that there is a second family of quarks and leptons: the 'charm' and 'strange' quarks and the muon and muon neutrino.

to as the 'up' and 'down' quarks. Roughly speaking, a proton is composed of two 'up' (u) quarks and one 'down' (d) quark. Since u quarks carry 2/3 units of electric charge (the unit is chosen so that electrons have a charge of –1) and d quarks carry –1/3 charge, protons have one unit of charge. Neutrons, on the contrary, are neutral and are made up of one u and two d quarks. There is a symmetry called isospin which places the pair of nucleons, i.e. protons and neutrons, on a similar footing. (This is analogous to the two possible states of a spin 1/2 system). At a deeper level, the isospin symmetry can be traced to a similar relationship between the u and d quarks. Note that there is a difference of one unit of charge between the u and d quarks forming the isospin doublet. To this pair, we may add a lepton doublet consisting of an electron neutrino (ν_e with 0 charge) and an electron (e^- with –1 charge). Our universe consists mostly of (u, d) quarks and (ν_e, e^-) leptons.

By the seventies, it became clear that there are more species of quarks and leptons. For instance, there is the muon μ^-, with properties similar to the electron, but about 207 times more massive. There is a neutrino ν_μ which goes with it. Further, there are two other quarks which are picturesquely referred to as the 'strange' quark (s with –1/3 charge) and the 'charm' quark (c with 2/3 charge). So we add the (c, s) quarks and the (ν_μ, μ^-) leptons to our collection of elementary particles. The nucleons have a mass* of about 0.94 GeV/c^2 while electrons have a mass of 0.51 MeV/c^2. Neutrinos are believed to be either strictly massless or have very tiny masses, while the s and c quarks are more massive than the u and d quarks. It is a bit difficult to talk about the masses of the quarks since free quarks are never seen. (It is believed that quarks are permanently confined within a strongly interacting particle such as a nucleon). Nevertheless, it is possible to estimate 1/3 GeV/c^2 as being the approximate effective mass for the u and d quarks, 1/2 GeV/c^2 for the s quark, and nearly 1.5 GeV/c^2 for the c quark. The first indication of the c quark was a bound state cc (made out of a c quark and its antiparticle c) with a mass of about 3.1 GeV/c^2 which was observed at Stanford in 1974 in positron-electron (e^+e^-) collisions. This was confirmed at Brookhaven

In 1975 the discovery of the tau lepton indicated the existence of a third family of quarks and leptons. The tau neutrino was inferred and the 'bottom' quark was seen soon after, and the quest for the missing 'top' quark began in right earnest.

* MeV, GeV and TeV denote energies equal to 10^6, 10^9 and 10^{12} electron volts respectively. The masses of elementary particles are often quoted in units of energy/c^2 following Einstein's famous equation $E = mc^2$ where c denotes the speed of light. 1 GeV/c^2 corresponds to a mass of about 1.78×10^{-27} kg.

The Basic Constituents of Matter

These consist of six quarks and six leptons. They are listed below in three families, with their charges. The recent discovery of the 'top' quark (*t*) is important because it completes this list of quarks.

	Leptons		Quarks	
Charge	–1	0	2/3	–1/3
Family 1	electron e	electron neutrino ν_e	'up' quark u	'down' quark d
Family 2	muon μ	muon neutrino ν_μ	'charmed' quark c	'strange' quark s
Family 3	tau τ	tau neutrino ν_τ	'top' quark t	'bottom' quark b

(ν_τ has not yet been directly detected)

soon afterwards in proton-proton collision experiments.

In the late seventies, there was an indication that there could be one more set of quarks and leptons. The first to be discovered, in 1975, was the heavier brother (sister?) of the electron and the muon. The τ lepton has a mass of 1.784 GeV/c^2 and there is a related neutrino ν_τ. We can expect this lepton doublet to be accompanied by a quark doublet. In 1977, a new quark called 'bottom' (*b*) was seen in the bound state $b\bar{b}$ in e^+e^- collisions at about 10 GeV total energy. The *b* quark has –1/3 charge. Naturally the quest began for its partner quark called 'top' (*t*) which should have 2/3 charge. This doublet (*t, b*) would then form the third generation of quarks. (The discoverers of the neutrino and τ, Reines and Perl, were awarded the Nobel Prize for physics in 1995).

We need high-energy projectiles to be able to produce the heavy 'top' quark. In fact, there was no clue as to how massive the *t* quark would be. With the commissioning of each new high energy accelerator, attempts were made to scan through the available energy range for a possible sighting of the *t* quark. And as the *t* quark remained elusive, the lower limit for its mass kept going up. Further, since there are many channels for scattering reactions at high energies, searching for the *t* quark signal was like looking for a needle in a haystack — a laborious and complicated process. A faint clue came from another important experiment. The precision measurements on the *Z* bosons, which were copiously produced at the Large Electron Positron (LEP) collider at CERN, Geneva, suggested a possible range for the t quark mass in the interval 150-200 GeV/c^2. The final proof came in the experiments done in the last two years at Fermilab near Chicago in the Tevatron collider (so named because this machine can reach a total energy of 1 TeV). In the Tevatron, protons and antiprotons of total energy 900 GeV collide to produce various kinds of states which are then analysed by two gigantic detector systems called D0 (D zero) and CDF (Collider Detector Facility). Each system is operated by a team of about 400 physicists from about 40 laboratories in the world (D0 includes TIFR, Panjab and Delhi Universities). Both experimental groups have now announced that they see candidate events which can be regarded as observations of the t quark. Typically, the bound state tt which is produced decays yielding $W^+ W^- bb$. (The W^+ W^- and Z bosons are the carriers of the weak interactions just as the photon is the carrier of the electromagnetic interactions among quarks and leptons). The strategy for detection was to look for events when both the W particles decay giving rise to ee^+ jets, $e\mu^+$ jets and $\mu\mu^+$ jets, or when one of the W's decays producing e^+ jets and μ^+ jets. The jets are produced by the b quark and by the subsequent chain of heavy quarks which result from successive decays. The D0 team reports 17 candidate events with an expected background (noise) of 3.8 $\pm$ 0.6 events. The mass of the t quark is measured to be 199 $\pm$20 (stat) $\pm$ 22 (syst) GeV/c^2, the uncertainties arising from possible statistical and systematic errors. The CDF group finds the t quark mass to be 176$\pm$8 (stat) $\pm$10 (syst) GeV/c^2.

With this observation, we seem to have three generations of quarks and leptons. Independently, by studying the life-time of the Z boson, we can deduce the number of species of neutrinos into which Z can decay. The result of the analysis strongly suggests that the number of generations (with one species of ν for each generation) is just three. Perhaps there are no more quarks or leptons to be discovered. The 'top' may be the last elementary particle.

Searching for the 'top' quark signal was like looking for a needle in the haystack. But experiments carried out at the Tevatron collider at Fermilab in 1994-95 now provide the final proof of the existence of the 'top' quark.

While the 'top' discovery filled the missing piece in the set of basic constituents of matter, it has also raised many questions. For instance, why is 'top' so much heavier than the other quarks? This makes the 'top' quark extremely 'short lived' and throws up new puzzles to be solved. Further research is needed to understand the properties that 'top' shares with other quarks and the ways in which it is different from them.

R Ramachandran is at the Institute of Mathematical Sciences, Madras 600 113.