

Box 1: How do you recognize a vertebrate?

All living vertebrates share a relatively small number of characters found in no other group, which are assumed to have been inherited from a common vertebrate ancestor. All these characters are made of initially non-mineralized tissues (including cartilage) and are thus unlikely to be preserved in very early fossil vertebrates. The two Early

Cambrian fossils from China display some vertebrate characters directly, whereas others can be inferred. Both show a dense imprint of what is probably a cartilaginous skull, one of the main vertebrate features. The gill skeleton may be indirect evidence for a neural crest, the main vertebrate character. The fin rays (radials) in one of the

two forms and a large heart, lying behind the gills and possibly enclosed in a pericard, are also unique vertebrate characters. Chevron-shaped muscle blocks also occur in cephalochordates (the closest living relatives of vertebrates), but have a more complex zigzag shape in vertebrates, as can be clearly seen in at least one of the fossils. **P. J.**

than to any other vertebrate group, whereas the other appears as the sister-group to all other vertebrates but hagfishes (Fig. 1). The support for this result is admittedly tenuous; morphology-based data matrices for fossil vertebrate groups include a large number of question marks, because of missing data in fossils and uncertainties as to the interpretation of some of the soft-tissue characters seen in imprints. This is true for the two Cambrian fish. Nevertheless, the result makes broad sense, because it suggests that lampreys and their fossil relatives had diverged already in the Cambrian, as predicted by previous phylogenies.

Lacking fossils, palaeontologists and anatomists have often tried to imagine the earliest vertebrates. The two new fossils from China resemble some of these imaginary reconstructions, but are completely at odds with others. Were theoretical reconstructions

of the ancestral vertebrate partly accurate, or do we pay special attention to fossils that resemble the reconstructions in our minds? ■

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Particle physics

Maxwell's other demon

Frank Wilczek

Worrying over Maxwell's demon¹ has sharpened our understanding of the asymmetry between past and future in thermodynamics². In his lecture opening the Cavendish Laboratory in Cambridge³, Maxwell touted another demon, the Devil in the Details: "The history of science shows that even during that phase of her progress in which she devotes herself to improving the accuracy of the numerical measurements of quantities with which she has long been familiar, she is preparing the materials for the subjugation of new regions, which would have remained unknown if she had been contented with the rough methods of her early pioneers".

In rendering homage to Maxwell's other demon, physicists are again sharpening their understanding of the asymmetry between past and future, this time as it relates to the

interactions of elementary particles. The details arising from careful experiments^{4,5} and new calculations⁶ are proving surprisingly difficult to reconcile.

In the past few months, experimenters at Fermilab⁴ in the United States and at CERN⁵ in Europe announced results from their delicate, long-running, heroic experiments to measure CP violation — the asymmetry responsible for the dominance of matter over antimatter in the Universe (Box 1). To establish CP violation, particle physicists compared rare decay modes of exotic particles known as kaons. Their results are consistent with each other and with some earlier, less precise measurements⁷. They measure a critical parameter, r , describing these rare events to be $21 (\pm 4.6) \times 10^{-4}$.

The fact that r differs from zero at last puts to rest the 'superweak' model of CP vio-

lation⁸, which postulated a superweak interaction outside the Standard Model of particle physics. This is a milestone achievement, but it hardly comes as a surprise. The Standard Model beautifully accommodates the phenomenon of CP violation⁹, and it predicts quite a different, richer pattern of effects from the superweak model. Indeed, the Standard Model supplies plausible answers to two of the deepest questions this phenomenon poses: why is CP — or equivalently T — violated and why are its effects so hard to observe?

According to our current best understanding, CP violation emerges as a rather accidental by-product of the simplicity of the Standard Model. Defining a symmetry for a set of equations (that is, physical laws) means transforming the various terms in these equations, in such a way that the content of the transformed equations is precisely the same as that of the original ones. The attempt to define a symmetry in this way will fail only if one runs into a conflict — if one term in the equations requires you to transform a quantity in one way, and another term makes a different demand. It turns out that the equations of the Standard Model are so simple that they have little potential for conflict. Indeed, if there were only two families of quarks and leptons, CP and T would be automatic. In a brilliant piece of theoretical physics, Kobayashi and Maskawa⁹ understood this, and used it to argue that there ought to be a third family. At the time, only two families — the *ude* family containing up and down quarks and electrons, and the *cs μ* family containing charm and strange quarks and muons — were known. Sure enough, the third *tb τ* family containing top and bottom quarks and tau leptons duly materialized.

The fact that in the Standard Model, CP

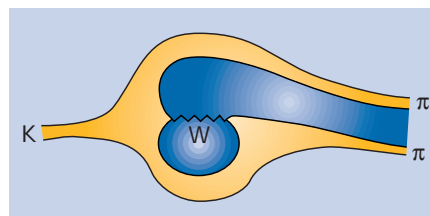


Figure 1 Many calculations in the Standard Model are neatly summarized by pictures — known as Feynman graphs — that follow the trails of virtual particles in space and time. According to Blum *et al.*⁶, the dominant contribution to the CP violation defined by r in the Standard Model comes from the Feynman graph shown above. For obvious reasons, this is called the 'eye graph'. It describes the underlying motion of quarks, antiquarks (straight lines) and a virtual W boson (zigzag) as a kaon (K) decays into two pions (π). Although eye-graph dominance comes as something of a surprise to many theorists, it could help resolve a long-standing puzzle, the so-called $\Delta I = \frac{1}{2}$ rule (don't ask!).

Box 1: Charge, Parity and Time

According to CP symmetry, the laws of physics will appear the same if you simultaneously interchange left and right (for example, reflect in a mirror) and change all particles into their antiparticles. Part of the appeal of CP symmetry is that general principles of quantum mechanics and relativity suggest that CPT — which does these transformations, and also reverses the direction of motion of all particles, or equivalently reverses the arrow of time — is a valid symmetry of nature. Assuming this, CP is then equivalent to T (ref. 15). So in testing CP symmetry, one is testing the proposition that the fundamental laws of nature do not distinguish between past and future. (Of course, this is a very different thing from saying that *the world* does not

distinguish between past and future.)

The classic laws of gravity and electromagnetism certainly do possess time-reversal or T symmetry, and the search for CP violation was fruitless for many years. Then Cronin, Fitch and colleagues¹⁶ discovered a small effect in kaon decays that is inconsistent with CP symmetry. Specifically, they found that among long-lived neutral kaons, K_L , which usually decay into three pions, about one in 1,000 particles decay into two pions ($\pi\pi$). If CP were exactly valid, that would never occur. (This is not supposed to be obvious — the argument is subtle, but quite firm.)

It has proved very difficult to improve on Cronin and Fitch. Prior to some very recent

experiments^{4,5,17}, the only firm evidence for CP violation was from kaon decays, and all of it was consistent with the 'superweak' proposal that K_L contained a small admixture of the short-lived kaon K_S , which normally decays into two pions.

The latest measurements refine Cronin and Fitch by comparing the two different possibilities for $K_L \rightarrow \pi\pi$: the pions can either be one positive and one negative, or alternatively both electrically neutral. If the superweak idea is correct, these two possibilities will occur in exactly the same ratio as they do in K_S decays. The actual ratio of ratios is defined to be $1 + 6r$. So if $r \neq 0$ the superweak proposal is wrong, and there's more to CP violation than a tainted K_L . **F. W.**

(or T) violation arises only from effects of the third family explains why its effects are ordinarily so small. We usually study matter made out of just the first two families, so the only CP-violating effects occur through the small, indirect influence of virtual heavy particles from the third family. Ambitious plans are afoot to study particles containing *b* quarks directly. When such particles decay all three families are actively in play, and CP-violating effects are expected to be accessible¹⁰.

What does the Standard Model predict for *r*? This has been the object of some controversy. A major review of the subject¹¹ quotes $r = 7.7 \times 10^{-4}$, but allows for values from 4.2×10^{-4} to 13.7×10^{-4} . The reason for the spread in this prediction is revealing. Uncertainty arises not so much from any defect in fundamental theory or ignorance of fundamental parameters in the Standard Model, but from weaknesses in our ability to calculate its consequences. For example, there is no simple, reliable way to solve the equations of QCD (quantum chromodynamics) with good accuracy. In making their estimates, theorists resort to rather crude models and drastic approximations, which can come to resemble art more than science.

Into the breach have rushed the number-crunchers, creating a bombshell⁶. By solving the equations of QCD numerically, using ultrafast parallel computers, one obtains, in principle, definitive answers. A group of researchers from Columbia University and Brookhaven National Laboratory now reports that the Standard Model predicts *r* to be negative — actually, $-120 (\pm 70) \times$

10^{-4} — in dire contradiction with the experimental result. Their result reinforces earlier hints of trouble from less definitive numerical work¹². Moreover, they suggest that the difference between these calculations and previous predictions lies in their treatment of a particular process described by the 'eye graph' shown in Fig. 1.

Because the source of CP violation in the Standard Model is in principle well understood and in some sense small, experiments

Genomics

Functional links between proteins

Andrej Šali

Genome-sequencing projects have accomplished a monumental feat in generating complete lists of the proteins that make up multi-subunit assemblies and signalling pathways in various organisms. These assemblies and pathways must now be mapped, and papers by Marcotte *et al.*¹ and Enright *et al.*² (pages 83 and 86 of this issue) take a significant step in this direction. The two groups have developed computational methods that associate proteins through properties other than the similarity between their amino-acid sequences. By comparing phylogenetic (evolutionary) profiles and expression patterns, as well as by analysing domain fusions, the new methods identify proteins that are functionally linked

in CP violation are especially sensitive to physics outside the Standard Model. Indeed, popular supersymmetry models feature so many potential new sources of CP violation that it is somewhat embarrassing that no deviation from the Standard Model has been observed (until perhaps now). Supersymmetry implies the existence of particles even heavier than the particles in the third family, although there is no evidence for them yet.

As always, extraordinary results merit extraordinary scrutiny. If the Columbia/Brookhaven result holds up, the value of *r* will join neutrino oscillations¹³ as the first indications of physics beyond the Standard Model. Already there are serious proposals for how it might be tied up with supersymmetry¹⁴. ■

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