random fields, or what physicists call 'free fields'. Thus the effects of the missing fluctuations can be computed analytically and added back in.

The approximation of finite volume is mitigated by the fact that in QCD the fundamental interactions occur among field variables at neighbouring points (we say they are local interactions). The patterns of equilibrium that define hadrons are, however, generally spatially extended, and so it is important to take a large enough volume so they fit comfortably. It is possible to control finite-volume errors by varying the simulated volume and making theoretically informed extrapolations.

Two additional approximations have also proved unavoidable, and troublesome, in practice. One is that as the *u* and *d* quark masses are taken down to their (very small) physical values, the equations get harder to solve. (For experts: this is because there are long correlation lengths, and the equations become numerically 'stiff'.) Like the compromise of assuming a finite volume, this is handled by sophisticated, theoretically informed extrapolation from simulations using larger mass values. Finally, even after acceptable levels of discretization and restriction to finite volume, the space that should be surveyed by the wavefunction is far too large for even the most powerful modern computer banks to handle. So in place of a complete survey, we must content ourselves with a statistical sample of the wavefunction. This introduces errors that can be estimated by the standard techniques of statistics.

For optimal use of resources, one should bring all the important sources of error to the same level. This involves a delicate balancing act. For example, using larger volumes or smaller quark masses requires lengthier calculations, which degrade the sampling rate of the wavefunction. The technical feat of Dürr *et al.*[1] is to achieve such a balance, keeping all the errors demonstrably small.

Of course, overwhelming evidence for the validity of QCD has been accumulating for decades, from very different sorts of calculations and experiments. Although quarks and gluons do not exist as isolated particles, they can be reconstructed from the patterns of energy–momentum flow they imprint on hadrons. In high-energy collisions, the emerging hadrons are found to be organized into jets of particles moving in approximately the same direction as each other. According to QCD, if we replace the jets by fictitious single particles with the same total energy and momentum as the jets, those fictitious particles will obey the equations of elementary quarks and gluons. This is another aspect of asymptotic freedom. Through the study of jets, the basic equations of QCD have been verified in exquisite detail.

So what value is added by using already-validated equations to compute already-measured hadron masses? One answer is practical. The same techniques that are used to compute known hadron masses can also be used to compute other interesting quantities that are very difficult to measure experimentally. For example, some key reactions involving small nuclei and unstable particles (hyperons) are very important in stellar nucleosynthesis and supernova dynamics, but are impracticable to measure. Having numerical techniques that reliably reproduce what is known, we can address the unknown confidently.

But perhaps a more profound answer is philosophical. A great vision of science — stretching from Pythagoras' credo "All things are number", to Kepler's ordering of the planets based on Platonic solids, to Wheeler's slogan "Its from bits" — has been that physical reality embodies ideally simple mathematical laws. As physics developed before the quantum revolutions of the twentieth century, the basic equations emphasized dynamics (how given systems evolve in time) as opposed to ontology (the science of what exists). Kepler's system was stillborn, but in the world of QCD and hadrons, the great vision lives and thrives.

Finally, let me add a note of critical perspective. The accurate, controlled calculation of hadron masses is a notable milestone. But the fact that it has taken decades to reach this milestone, and that even today it marks the frontier of ingenuity and computer power, emphasizes the limitations of existing methodology and challenges us to develop more powerful techniques. QCD is far from being the only area in which the challenge of solving known quantum equations accurately is crucial. Large parts of chemistry and materials science pose similar mathematical challenges. There have been some remarkable recent developments in the simulation of quantum many-body systems, using essentially new techniques[5]. Can the new methods be brought to bear on QCD? In any case, it seems likely that future progress on these various fronts will benefit from cross-fertilization. The consequences could be enormous. To quote Richard Feynman[6]: "Today we cannot see whether Schrödinger's equation contains frogs, musical composers, or morality — or whether it does not. We cannot say whether something beyond it like God is needed, or not. And so we can all hold strong opinions either way." ■

Frank Wilczek is in the Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02142, USA.
e-mail: wilczek@mit.edu

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PALAEONTOLOGY

Turtle origins out to sea

Robert R. Reisz and Jason J. Head

Various aspects of turtle evolution are the subject of vigorous debate among vertebrate palaeontologists. A newly described fossil species, the oldest yet discovered, adds grist to the mill.

During the Late Triassic, some 220 million years ago, primitive turtles about 40 centimetres in length were preserved in sedimentary deposits in what is now southwestern China. These fossils are examples of a new species of a very early turtle, named *Odontochelys semitestacea*, which is described by Li *et al.* on page 497 of this issue[1] and which will change ideas about turtle origins and the evolution of their striking body plan.

Turtles are remarkable animals[2]. They have a horny beak rather than teeth, and a shell like that of no other animal, one that is composed of an upper carapace and a lower plastron, jointed together by a bony bridge. The shell is a composite structure derived from ribs, parts of the shoulder girdle and specialized dermal bones. This precludes the typical costal respiration of tetrapods, in which movable ribs allow the chest cavity to expand and contract. Turtles have overcome this obstacle by having the muscles that control breathing use the limb pockets at the borders of the shell. This shell has become modified as turtles diversified and adapted to terrestrial, amphibious and aquatic environments (Fig. 1). The evolutionary relationships and ecology of turtles through time, and the developmental and evolutionary origins of the shell, are major controversies in studies of vertebrate evolution.

Previously, the fossil evidence for turtle origins came largely from *Proganochelys quenstedti* from Germany, which lived between 204 million and 206 million years ago, and other less-well-known early turtles. *Proganochelys* is known from several skeletons. It has a massive shell and spiked armour on the neck and tail, but also retains teeth on the roof of the mouth and has other primitive features in the skull and skeleton. Its osteology has been used to propose[3] that turtles are related to pareiasaurs, a group of extinct parareptiles that includes species with extensive dermal armour. And on the basis of evidence from *Proganochelys*

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Figure 1 | Differences in turtle ecology. There are about 300 extant species of turtle, which vary in weight from about 100 grams to about 860 kilograms, and whose habitat ranges from wet meadows to deserts, and from rivers and lakes to the open ocean. Top, a fully terrestrial turtle (*Gopherus agassizii*), representing a similar ecology to that of the primitive turtle *Proganochelys* and its relatives inferred in previous studies[4,5]. Bottom, an aquatic turtle (*Apalone spinifera*), representing a potentially similar ecology to that of the fossil species *Odontochelys semitestacea* described by Li and colleagues[1].

and its close relatives from the Late Triassic of Argentina, Germany and North America, it has been suggested that the earliest turtles lived in terrestrial environments[4,5].

The discovery and description of *Odontochelys* by Li *et al.*[1] challenges these hypotheses. *Odontochelys* is not only the oldest recognizable turtle, but its skull also shows that it is more primitive than other turtles because it retains a full complement of marginal teeth, rather than a beak, and also possesses free sacral ribs and a long tail. Its osteology contradicts the view that turtles have pareiasaurian affinities, and, along with molecular data, supports evolutionary hypotheses that they are closely related to another group, the diapsid reptiles[6,7]. Li *et al.* argue that *Odontochelys* represents an early stage in the evolution of the turtle shell because the plastron is present and fully developed, but the carapace is apparently absent, with only dorsal ribs and neural (midline) dermal ossifications present. The authors infer, therefore, that the plastron evolved before the carapace, reflecting the timing of shell ossification during embryonic development in living turtles.

Although this evolutionary scenario is plausible, we are particularly excited by an alternative interpretation and its evolutionary consequences. We interpret the condition seen in *Odontochelys* differently — that a carapace was present, but some of its dermal components were not ossified. The carapace forms during embryonic development when the dorsal ribs grow laterally into a structure called the carapacial ridge, a thickened ectodermal layer unique to turtles[8]. The presence of long, expanded ribs, a component of the carapace of all turtles, indicates that the controlling developmental tissue responsible for the formation of the turtle carapace was already present in *Odontochelys*. The expanded lateral bridge that connects the plastron to the carapace in other turtles is also present, implying that the plastron was connected to the laterally expanded carapace. Thus, an alternative interpretation is that the apparent reduction of the carapace in *Odontochelys* resulted from lack of ossification of some of its dermal components, but that a carapace was indeed present.

This interpretation of *Odontochelys* leads us to the possibility that its shell morphology is not primitive, but is instead a specialized adaptation. Reduction of dermal components of the shell in aquatic turtles is common: soft-shelled turtles have a greatly reduced bony shell and have lost the dermal peripheral elements of the carapace. Sea turtles and snapping turtles have greatly reduced ossification of the dermal components of the carapace, a condition similar to that seen in *Odontochelys*.

From the geological context of their fossils, Li *et al.*[1] conclude that *Odontochelys* lived in a shallow marine environment. That, combined with similarities between its carapace and the reduced shells of modern aquatic turtles, leads us to propose that the absence of most of the dermal carapace in *Odontochelys* is a secondary loss associated with aquatic habits rather than a primitive condition, as inferred by Li and colleagues. Given the similarities between its shell morphology and early growth stages in living turtles, a simple truncation of carapace ossification, in which the adults retained juvenile features (paedomorphosis), could have been a developmental mechanism in the evolution of the reduced carapace.

Regardless of the primitive or derived nature of its shell, *Odontochelys* is in evolutionary terms the most 'basal' turtle yet found. Its discovery opens a new chapter in the study of the origins and early history of these fascinating reptiles. Both interpretations alter our views of turtle evolution: *Odontochelys* either represents the primitive ecology for turtles, consistent with the hypothesis that the turtles' shell evolved in aquatic environments[7], or it represents the earliest turtle radiation from terrestrial environments into marine habitats. Either way, these ancient turtles demonstrate yet again the value of new fossil discoveries in changing our understanding of vertebrate history. ■

Robert R. Reisz and Jason J. Head are in the Department of Biology, University of Toronto Mississauga, Mississauga, Ontario L5L 1C6, Canada.
e-mail: robert.reisz@utoronto.ca

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ORGANIC CHEMISTRY

Short cuts to complexity

André B. Charette

The credit crunch is forcing people to tighten their belts, but chemists have long known the benefits of being economical with atoms. The latest synthesis of an anticancer agent shows how effective parsimony can be.

Nature produces an almost infinite number of structurally complex organic compounds that have fascinating — and potentially useful — biological properties. This has inspired generations of synthetic chemists to make not only the naturally occurring compounds, but also structurally modified analogues that have tailored properties and functions. Marine organisms are a particularly rich source of natural products, but so far only one such class of compound has entered clinical trials: bryostatins, which have anticancer activity *in vivo*[1]. Reporting in this issue (page 485), Trost and Dong[2] describe a synthetic route to a particular bryostatin — bryostatin 16 — that drastically reduces the longest sequence of consecutive steps from the previous best of 40 down to a much more manageable 26. This might open