probably prove less controversial than their interpretations of the associated geodynamic events. For example, the idea that the break-up of Gondwanaland was caused by a large mantle plume is contentious. Data on the ages of certain circum-Indian Ocean basalt rocks and of the oldest Indian Ocean sea floor suggest that the split of India from Australia and Antarctica occurred about 130 million years ago. With one small exception, that precedes evidence of plume activity, in the form of large-scale emplacements of igneous rocks, by at least 10 million years[6]. The assumption that large-scale, sub-continental melting is necessarily caused by mantle plumes has also been challenged[7], with the suggestion that continental aggregation may promote such melting without the involvement of a plume. Even though the timing and circumstances of the loss of India's lithospheric roots will remain controversial, one thing is sure: Archaean lithosphere is not for ever. ■

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STRING THEORY

Back to basics

Hermann Nicolai

Long touted as a theory of everything, it seems that string theory may at last succeed as a theory of something very specific — the interactions of particles under the strong nuclear force.

Whether string theory can live up to its claim of being a 'theory of everything', and whether it will ever produce a falsifiable prediction as such, remain hotly debated questions. Meanwhile, developments in a quieter side-alley[1–8] indicate that the theory might be about to deliver something of its original promise: helping us to understand the physics of interactions mediated by the strong nuclear force.

String theory was born in the 1960s, when physicists tried to put order into a bewildering wealth of phenomena appearing at subnuclear distance scales. Here, the strong interaction dominates the other three fundamental forces of nature: gravity, electromagnetism and the weak nuclear interaction. Scattering experiments in high-energy particle accelerators had revealed a stunning proliferation of resultant particle-like excitations — 'resonances' — at particular energies, amounting to an ever-growing zoo of particles that could not possibly all be elementary (that is, indivisible).

It soon became apparent that the strongly interacting particles (also known as hadrons) could be ordered into certain symmetrical patterns akin to the periodic table of the elements. Together with evidence from scattering experiments that the most familiar hadrons — the protons and neutrons (nucleons) of the atomic nucleus — had a spatially extended structure, this finding led to the insight that hadrons are made from smaller particles, the quarks. But initial attempts to describe the forces between the quarks, and why they form the bound states they do, failed miserably.

So particle physicists started casting around for other ways of attacking the problem. In 1968, the Italian theoretician Gabriele Veneziano made a brilliant guess[9] and wrote down a concrete mathematical expression, the Veneziano amplitude, that explained some important features of high-energy scattering. But his formula could not be understood in terms of point-like particles; instead, it required the existence of extended objects — strings. These strings are thin tubes of energy formed by force lines that bind quarks together, and, just like violin strings, they can oscillate in many modes. The numerous resonances of strong-interaction physics would then be nothing but the different oscillation modes of these strings.

Unfortunately, this theory soon turned out to have several flaws, most seriously that, for mathematical consistency, a string must move in 25 spatial dimensions, rather than the familiar three. A rescue attempt, replacing the string with a new 'fermionic' variety with infinitesimal particle spins attached to the tubular-force lines, brought the 25 dimensions down to 9 — better, but still not good enough[10,11].

The arrival in the early 1970s of quantum chromodynamics (QCD), the quantum-field theory of the strong interaction, dealt the final blow to these early attempts to understand nuclear physics in terms of string theory. But, unfortunately, QCD is incredibly complex. Except for a few showpiece calculations — which put to rest any doubts that QCD might not be a correct description of the strong force — it is extremely difficult to extract measurable consequences from it. One of these calculations is the proof of 'asymptotic freedom', according

NATURE

50 & 100 YEARS AGO

50 YEARS AGO

'Orbit of the artificial Earth satellite' — By a considerable feat of improvization, Mr. Martin Ryle and his team at the Mullard Radio Astronomy Observatory near Cambridge have been able to record the radio signals transmitted by the artificial satellite from October 5...
A report from the United States gives the maximum height of the orbit above the Earth as 583 miles and the minimum as 143 miles, and states that the carrier rocket was travelling three minutes ahead of the satellite on October 12...
Mr. D. H. Sadler reports... that the carrier rocket is now visible in the British Isles in the morning twilight... On October 13 it was approximately over Bournemouth at 5h. 26m. U.T., the track moving south-west, parallel to itself, about 200 km. a day.

From *Nature* 19 October 1957.

100 YEARS AGO

'Classification of portraits' — Experiments of various kinds that I have made to define the facial peculiarities of persons, families, and races by means of measurement led to the following results... The individuality of a portrait lies more in the relative positions of six cardinal features than in the shapes of the lines that connect them... The features are these:— *c*, the tip of the chin; *l*, the lower, and *u*, the upper lip; *m*, the hollow between the upper lip and the nose; *n*, the tip of the nose; *f*, the hollow between the nose and the brow... In my experiments I have chiefly used the side-view portraits by George Vance, R. A., of his distinguished contemporaries, published in 1809... I lexiconised these in respect to the measures...and found, first, that no two of the numerical formulae were the same... I have applied the above method to portraits of very different races, and have thus far found it efficient in all of them.
Francis Galton

From *Nature* 17 October 1907.

to which strong interactions become weak at very short distances. In this 'perturbative' regime, we understand (at least in principle) how to work with QCD. But for the strong coupling that occurs over larger distances, one has to resort to computer-simulation techniques, known as lattice QCD. These techniques have been rather successful (for instance, in explaining the spectrum of hadron masses), but rigorous results remain hard to come by: despite years of effort, we still cannot explain, for example, why there are no free, single quarks in nature. Such unresolved puzzles are coming into renewed focus with the scheduled start of experiments at the Large Hadron Collider at CERN in Geneva next year.

The new approach that revives the link to string theory first suggested itself in 1998, when Juan Martín Maldacena conjectured[12] a link between a close relative of QCD and a 'superstring' living in a ten-dimensional curved space-time. Although the theory in question, known as supersymmetric $N = 4$ gauge theory, is sufficiently different from QCD to be of no direct interest to experiment, the link raised the prospect of a general connection to some form of compactified string theory. This equivalence is now commonly referred to as the AdS/CFT (Anti-de-Sitter/conformal field theory) correspondence. If true, it would mean that string theory was originally not so far off the mark after all — its ingredients just need to be interpreted in the correct way.

The Maldacena conjecture raised a lot of interest, but seemed for a long time to be quantitatively unverifiable. This was because it takes the form of a duality in which the strongly coupled string theory corresponds to weakly coupled QCD-like theory, and vice versa. But to verify the duality, one would need to find a quantity to compare in a regime of intermediate coupling strength, and calculate it starting from both sides. No such quantity was obvious.

Help came from an entirely unexpected direction. Following a prescient observation[13], the spectrum of the $N = 4$ theory has been found[1,2] to be equivalently described by a quantum-mechanical spin chain of a type discovered by Hans Bethe in 1931 when modelling certain metallic systems. There are not many quantum-mechanical systems that can be solved analytically — the hydrogen atom is the most prominent example — but Bethe's *ansatz* immediately applied in a much wider context, and constructed a bridge between condensed-matter physics and string theory (in this context, see the recent News & Views article by Jan Zaanen[14] on the nascent connection to high-temperature superconductivity). Indeed, even though the mathematical description of the duality on the string-theory side is completely different from that on the condensed-matter side, a very similar, exactly solvable structure has been identified here as well[3–5].

Puzzling out the details of the exact solution is currently an active field of research. But in one instance, that idea had already been put to such a hard test that a complete solution now seems within reach. The context is a special observable entity, the 'cusp anomalous dimension', which was argued[6,7] to be ideally suited as a device to test whether string and gauge theory really connect. Some of its structure at strong coupling was also worked out. Just recently, Beisert, Eden and Staudacher[8] have extracted the analogue of this observable on the field-theory side, and have been able to write down an equation valid at any strength of the coupling. Since then, work has established that their 'BES equation' does indeed seem, for the first time, to offer a means of reformulating theories such as QCD as string theories.

Much still needs to be learned from this one exactly solvable case. There is justifiable hope that this solution will teach us how to go back to the physically relevant case of QCD and finally arrive at the long-sought dual description by a string theory. It may even take us closer to realizing the quantum-field theorist's ultimate dream, unfulfilled for more than 50 years: completely understanding an interacting relativistic quantum-field theory in the four space-time dimensions that we are familiar with. Progress towards this goal can be judged independently of loftier attempts to use strings in the construction of a theory of everything. ■

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MICROBIOLOGY

Preparing the shot

Christof R. Hauck

Direct injection of proteins into host cells is one of the tricks bacteria use during infection. It seems that, to achieve this, the stomach pathogen *Helicobacter pylori* first grabs the cell by its surface receptors.

The bacterium *Helicobacter pylori* successfully colonizes the stomach of about every third person. Infection with this ubiquitous micro-organism can cause acute and chronic gastritis, as well as stomach ulcers[1]. Moreover, up to 90% of cases of stomach cancer are associated with *H. pylori* infection. The bacterium's main weapon is an elaborate apparatus on its surface called the type-IV secretion system, which acts as a nano-syringe (Fig. 1a). Using this apparatus, the bacterium delivers a cancer-associated protein, CagA, directly into its host cells. But whether the bacterium anchors the secretion system to the surface of host cells before injection, and if so, how, has remained unclear. On page 862 of this issue, Kwok *et al.*[2] report that transfer of CagA is made possible by another *H. pylori* protein, CagL, which binds to integrin receptors on gastric epithelial cells.

So far, CagA is the only *H. pylori* protein known to be injected into the host cell. In the bacterial chromosome, the *cagA* gene is part of a stretch of DNA called *cag*PAI, which also encodes the structural components of the type-IV secretion machinery[3]. Bacterial strains harbouring *cag*PAI are considered to be more virulent than other strains[4].

Previous work[5–7] had shown that, once CagA is delivered into the host cell, kinase enzymes of the Src family add a phosphate group to it. The presence of phosphorylated CagA results in several changes that might promote *H. pylori* virulence and an unfavourable outcome for infection with this bacterium[4,8]. These changes include the assembly of signalling complexes, reduced cell–cell adhesion and induction of cell migration.

Examining the localization of phosphorylated CagA in isolated gastric epithelial cells, Kwok *et al.*[2] found that it occurs almost exclusively at focal adhesion sites — discrete regions of the cell where integrin receptors 'glue' cells to the supporting extracellular matrix. The authors speculated that CagA might not move through the cytoplasm of the infected cells to these sites, but instead be injected directly at these places. Support for this idea came from experiments demonstrating that CagA is not transferred into host cells if *H. pylori* cannot