The recent symposium at Minnesota, US, to celebrate 30 years of supersymmetry theory, attracted many key figures in the field.

Glimpses of superhistory

Nearly 30 years after its discovery, supersymmetry remains the prime candidate to cure all of the ills of our understanding of elementary particle behaviour. Putting aside the question of experimental evidence, a recent meeting looked at the history of supersymmetry.

The word according to Ed Witten

"Supersymmetry, if it holds in nature, is part of the quantum structure of space and time...The discovery of quantum mechanics changed our understanding of almost everything in physics, but our basic way of thinking about space and time has not yet been affected...Showing that nature is supersymmetric would change that, by revealing a quantum dimension of space and time, not measurable by ordinary numbers...Discovery of supersymmetry would be one of the real milestones in physics."

Supersymmetry is now 30 years old. The first supersymmetric field theory in four dimensions – a version of supersymmetric quantum electrodynamics (QED) – was found by Golfand and Likhtman in 1970 and published in 1971. At that time the use of graded algebras in the extension of the Poincaré group was far outside the mainstream of high-energy physics. Three decades later, it would not be an exaggeration to say that supersymmetry dominates high-energy physics theoretically and has the potential to dominate experimentally as well. In fact, many people believe that it will play the same revolutionary role in the physics of the 21st century as special and general relativity did in the physics of the 20th century.

This belief is based on the aesthetic appeal of the theory, on some indirect evidence and on the fact that there is no theoretical alternative in sight. Since the discovery of supersymmetry, immense theoretical effort has been invested in this field. More than 30 000 theoretical papers have been published and we are about to enter a new stage of direct experimental searches.

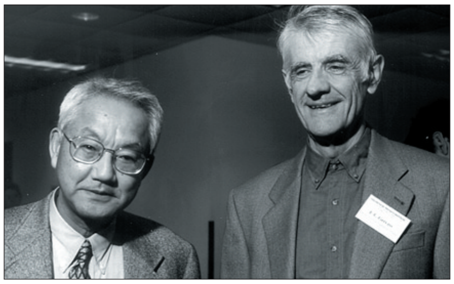
The largest-scale experiments in fundamental science are those that are being prepared now at the LHC at CERN, of which one of the primary targets is the experimental discovery of supersymmetry.

The history of supersymmetry is exceptional. In the past, virtually all major conceptual breakthroughs have occurred because physicists were trying to understand some established aspect of nature. In contrast, the discovery of supersymmetry in the early 1970s was a purely intellectual achievement, driven by the logic of theoretical development rather than by the pressure of existing data.

Simultaneous discovery

To an extent, this remains true today. The history of supersymmetry is unique because it was discovered practically simultaneously and independently on the both sides of the Iron Curtain. There was very little cross-fertilization – at least in the initial stages. As such, it is not surprising that eastern and western research arrived at this discovery from totally different directions.

While scientific interactions could have been mutually beneficial, they did not occur. Indeed, the political climate of the 1970s pre- ▷


Pioneers of supersymmetry (left to right): Vyacheslav Soroka, Evgeny Lichtmann, Vladimir Akulov, Bunji Sakita, Jean-Loup Gervais, Lochlainn O'Raifeartaigh, Pierre Fayet and John Iliopolous. This Minnesota meeting was one of O'Raifeartaigh's last public appearances before his death last year on 18 November (January px).

Superworkshop

Last October, Minnesota's Theoretical Physics Institute hosted a symposium and workshop celebrating 30 years of supersymmetry. The opening days featured many of the founding fathers of supersymmetry, including Evgeny Likhtman, Vladimir Akulov and Vyacheslav Soroka representing the Eastern origins of supersymmetry.

From the West, speakers included Pierre Ramond, Jean-Loup Gervais, Bunji Sakita, Pierre Fayet, John Iliopoulos, Lochlainn O'Raifeartaigh, Sergio Ferrara, Peter Van Nieuwenhuizen, Martin Sohnius, S James Gates, John Schwarz, Peter West and Gabriele Veneziano. These historically flavoured accounts of, or by, early participants whose successes and failures shaped the modern understanding of high-energy physics, were both emotional and instructive.

One focal presentation was the talk delivered by Mrs Koretz-Golfand, the widow of Yuri Golfand, who shared her recollections of her husband's life and work. This theme was continued by Evgeny Likhtman, Golfand's student. His talk combined anecdotal evidence with a summary of the Golfand–Likhtman results "before Wess–Zumino". It was also a remarkable testimony to how free scientific thought can resist the most oppressive of regimes.

For Evgeny Likhtman, this trip was his first to the West. The historical talks were intertwined with topical reviews devoted to the most exciting modern developments. The proceedings will be published by North–Holland.

cluded such interactions. Of course, once it was recognized that supersymmetry could be integrated into and extend the standard model of fundamental interactions, progress on both sides of the Iron Curtain were recognized. However, it was only recently that some of the pioneers who opened the gates to the superworld in the early 1970s met face to face for the first time – in Minnesota.

As so often when exploring new ground, some early work on supersymmetry was hit and miss. Golfand and Likhtman initially reported a construction of the super-Poincaré algebra and a version of massive super-QED. The formalism contained a massive photon and photino, a charged Dirac spinor and two charged scalars (spin-0 particles).

Likhtman found algebraic representations that could be viewed as supersymmetric multiplets and he observed the vanishing of the vacuum energy in supersymmetric theories. It is interesting to note that this latter work still only exists in Russian.

Subsequent to the work of Golfand and Likhtman, contributions from the East were made by Akulov and Volkov, who in 1972 tried to associate the massless fermion – appearing due to spontaneous supersymmetry breaking – with the neutrino. Within a year, Volkov and Soroka gauged the super-Poincaré group, which led to elements of supergravity. They suggested that a spin 3/2 graviton's superpartner becomes massive on "eating" the Goldstino that Akulov and Volkov had discussed earlier. The existence of this "super-Higgs mechanism" in full-blown supergravity was later established in the West.

A mathematical basis for the work of Volkov and collaborators was provided by the 1969 paper by Berezin and Katz (published in 1970), where graded algebras were studied thoroughly. In his memoirs, Volkov also mentions the impact of Heisenberg's ideas on the making of Volkov–Akulov supersymmetry.

In the West, a completely different approach was taken. A breakthrough into the superworld was made by Wess and Zumino in 1973. This work was done independently, because western researchers knew little if anything about the work done in the Soviet Union. The prehistory on which Wess and Zumino based their inspiration has common roots with string theory – another pillar of modern theory – which in those days was referred to as the "dual model".

Around 1969, the dual-resonance model of strong interactions, found by Veneziano, was formulated in terms of four-dimensional harmonic oscillators. Nambu advanced the idea that these oscillators represented a relativistic string. After that the scheme was reformulated as a field theory on the string world sheet. The theory was plagued by the fact that the spectrum contained a tachyon but no fermions and it was consistent only in 26 dimensions. These problems motivated the search for a more realistic string theory.

A leap into the superworld

The first success was achieved in 1971 by Ramond, who constructed a string analogue of the Dirac equation. Shortly afterwards, Neveu and Schwarz constructed a new bosonic string theory. They realized that the two constructions were different facets of a single theory – an interacting superstring theory containing Neveu and Schwarz's bosons and Ramond's fermions.

What are superparticles?

The known elementary particles come in two kinds – fermions, such as quarks, electrons, muons, etc (matter particles), and bosons, such as photons, gluons, Ws and Zs (force carriers). The key feature of supersymmetry is that every matter particle (quark, electron, etc) has a boson counterpart (squark, selectron, etc) and every force carrier (photon, gluon) has a fermion counterpart (photino, gluino, chargino, neutralino, etc). This doubling of the particle gene pool is because supersymmetry is a quantum-mechanical enhancement of the properties and symmetries of the space–time of our everyday experience, such as translations, rotations and relativistic transformations.

Supersymmetry introduces a new dimension – one that is only defined quantum mechanically and does not possess classical properties, such as continuous extent. The particle–superparticle twinning can assuage several theoretical headaches, such as why the different forces – gravity and electromagnetism – appear to operate at such vastly different and apparently arbitrary scales ("the Hierarchy Problem"). The extra particles provided by supersymmetry are also natural candidates for exotica, such as the missing dark matter of the universe.

Superglossary of terms

Anticommutators for two operators, P and Q, the anticommutator is {P,Q} = PQ + QP
Commutators for two operators, P and Q, the commutator is [P,Q] = PQ – QP
Dirac equation equation of motion for a Dirac spinor
Dirac spinor spin 1/2 particle with both left- and right-handed spin components
Higgs mechanism spontaneous symmetry breaking by means of the Higgs boson acquiring a vacuum expectation value
Poincaré group symmetry group that forms the basis of co-ordinate transformations in special relativity
Renormalizability the ability to "cleanse" a theory of mathematical divergences
Spontaneous symmetry breaking the breaking of a symmetry by states rather than interactions
Supergravity gauged supersymmetry. Just as supersymmetry is an extension of special relativity, supergravity is an extension of general relativity
Tachyon a particle that can move faster than the speed of light

In 1972 Schwarz demonstrated the consistency of the theory in 10 dimensions. It was in the study of this theory that algebras with both commutators and anticommutators first appeared in the western literature. A supersymmetry on the two-dimensional string world sheet was recognized by Gervais and Sakita in 1971. This property of the boson and fermion fields on the string world sheet was called the supergauge invariance, which was probably the first application of the prefix "super" in this context.

Four-dimensional string theory

The Gervais–Sakita supergauge invariance in two dimensions was the point of departure for Wess and Zumino. Starting in 1973, Wess and Zumino wrote a series of revolutionary papers that set the course for future research. Among these was the construction of a "modern" linear version of supersymmetry in four dimensions. They suggested a scalar-spinor model, which now goes under the name of the Wess–Zumino model. They also formulated the linear version of the supersymmetric extension to QED. In fact, as we know now, string theory contains local four-dimensional supersymmetry (supergravity), but string theorists were very slow to realize this.

The realization came only after supersymmetry in four dimensions was studied thoroughly. In these initial stages the geographic distribution of supersymmetry practitioners was very skewed. The lion's share of early research was carried out at CERN, Trieste, London and Paris. The name "supersymmetry" was coined by Salam and Strathdee in Trieste in 1974. It first appeared in the title of their paper that was devoted to supersymmetric gauge theories.

In the body of the paper they settled for the old-fashioned name, "supergauge". Subsequent progress was rapid. In a series of papers, Wess and Zumino; Iliopoulos and Zumino; and Ferrara, Iliopoulos, and Zumino described miraculous cancellations concerning the renormalizability of supersymmetric theories. The superspace/superfield formalism was worked out by Salam and Strathdee. Key non-renormalization theorems were proven by West and others.

Non-Abelian gauge theories were supersymmetrized, simultaneously, by Ferrara and Zumino; and Salam and Strathdee in 1974. Mechanisms for the spontaneous breaking of supersymmetry through F- and D-terms were found by O'Raifeartaigh; and Fayet and Iliopoulos. The foundations of what is now known as the minimal supersymmetric standard model were laid by Fayet.

Supergravity was being developed in parallel. This culminated in 1976 with the publication of two papers by Ferrara, Freedman and van Nieuwenhuizen; and Deser and Zumino. These authors assembled various "superelements" that were in circulation at that time, completing the elegant construction of modern supergravity.

A detailed account of the early history of supersymmetry can be found in *The Supersymmetric World: the Beginnings of the Theory*, which will be published soon by World Scientific.

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