When supergravity was born

Behind the most elegant, tricky or important calculations in physics can often lie some intensely personal and emotional challenges. **David Appell** looks at the pivotal moment in the life of Peter van Nieuwenhuizen when he proved the existence of "supergravity"

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A good calculation can be hard to find.

That is not the common view. Ask a non-scientist what a theoretical physicist does and you are likely to get a shrug of the shoulders along with a guess such as "scribbles equations all day?".

Even most physics students probably do not understand the lives of theorists. Students have problems handed to them, crisp and clean. Someone has already thought of the problem and found it doable, or it would never appear in the textbook. The answer exists; indeed, it is often in the back of the book. It's only a matter of applying the method in a straightforward manner and getting the algebra right.

If only physics was that easy *after* they award you the degree.

In real life, scientists spend much of their time groping in the dark, unsure even of what to do. "The hardest part of research is to decide exactly what question you're going to work on," theorist Edward Witten said in a 2010 lecture at the Institute for Advanced Study in Princeton, New Jersey. "If you ask too big a question," he continued, "you won't be able to answer it, and if you ask too little a question it's not worth doing. Even if you are working on a good problem, at the end of the day it seems like you've done nothing. You might have spent most of the day staring at a sheet of paper – I really mean it more or less literally. Or finding excuses for wasting time because you can't think of what else to do."

So after groping in the dark, after staring at the sheet of paper for a day or a month, the chance to calculate something can be both a relief, but also an ordeal. A relief, because one finally has something to do, a familiar way to think and to be, something one was trained to do. But also an ordeal, because mathematics can be hard work, with elegance found – if it is found at all – usually only after brute force has busted its way to an answer. As Albert Einstein – who knew about such things – once said, "God does not care about our mathematical difficulties. He integrates empirically."

Plunging boldly forward, theorists postulated a "supersymmetry" between fermions and bosons, but could it be applied to gravity?

Our story starts in 1975 when Peter van Nieuwenhuizen was a new professor at the Institute of Theoretical Physics at what was then the State University of New York at Stony Brook (now Stony Brook University). Fresh from a postdoctoral appointment at Brandeis University in Massachusetts, his new office was next to the institute's coffee machine, so colleagues often stopped in to chat after pouring a cup. One of them was Daniel Freedman, who, like Van Nieuwenhuizen, was interested in extending quantum field theory to include gravity. Their collaboration led to what Van Nieuwenhuizen calls "the most emotionally and physically wrenching calculation I ever did".

An eye for gravity

Gravity has always been the odd man left out of the physics party, which is ironic, it being the force we humans know best. It is long range and weak; as every student learns, the gravitational force between two electrons is 2×10^{-43} times smaller than the electrostatic force. Gravity is for planets, not particles.

Even worse, after Einstein was finished with it, gravity looked, smelled and tasted unlike the rest of physics. General relativity was a theory built on geometry, composed of the very properties of space–time itself. The gravitational theorists had their own journals, their own conferences and kept to themselves. Their mathematics looked weird – full of funny derivatives and Greek indices hanging like ornaments from a tree. And there was no point asking a particle physicist to do an experiment with gravity; for that you had to go talk to the astronomers, who wouldn't know a tensor if they tripped over one.

Not that the particle people didn't have their own problems. Ever since the earliest days of quantum electrodynamics in the 1940s – the theory that merges quantum mechanics with special relativity – theorists such as Richard Feynman, Julian Schwinger and Sin-Itiro Tomonaga found that their calculations of particle scatterings were plagued by infinities. Sadly for anyone trying to describe nature, "infinity" is always the wrong answer, as even the students know.

Various mathematical tricks were found to "renormalize" quantum electrodynamics so that its predictions were finite (and spot-on with experimental results, sometimes to a frightening number of decimal places), and theorists proceeded to build the now-famous Standard Model of particle physics, which unifies the electromagnetic, weak and strong forces. Theorists grew smug – successful predictions about the fundamentals of the universe will do that to you – and some turned their eyes to gravity.
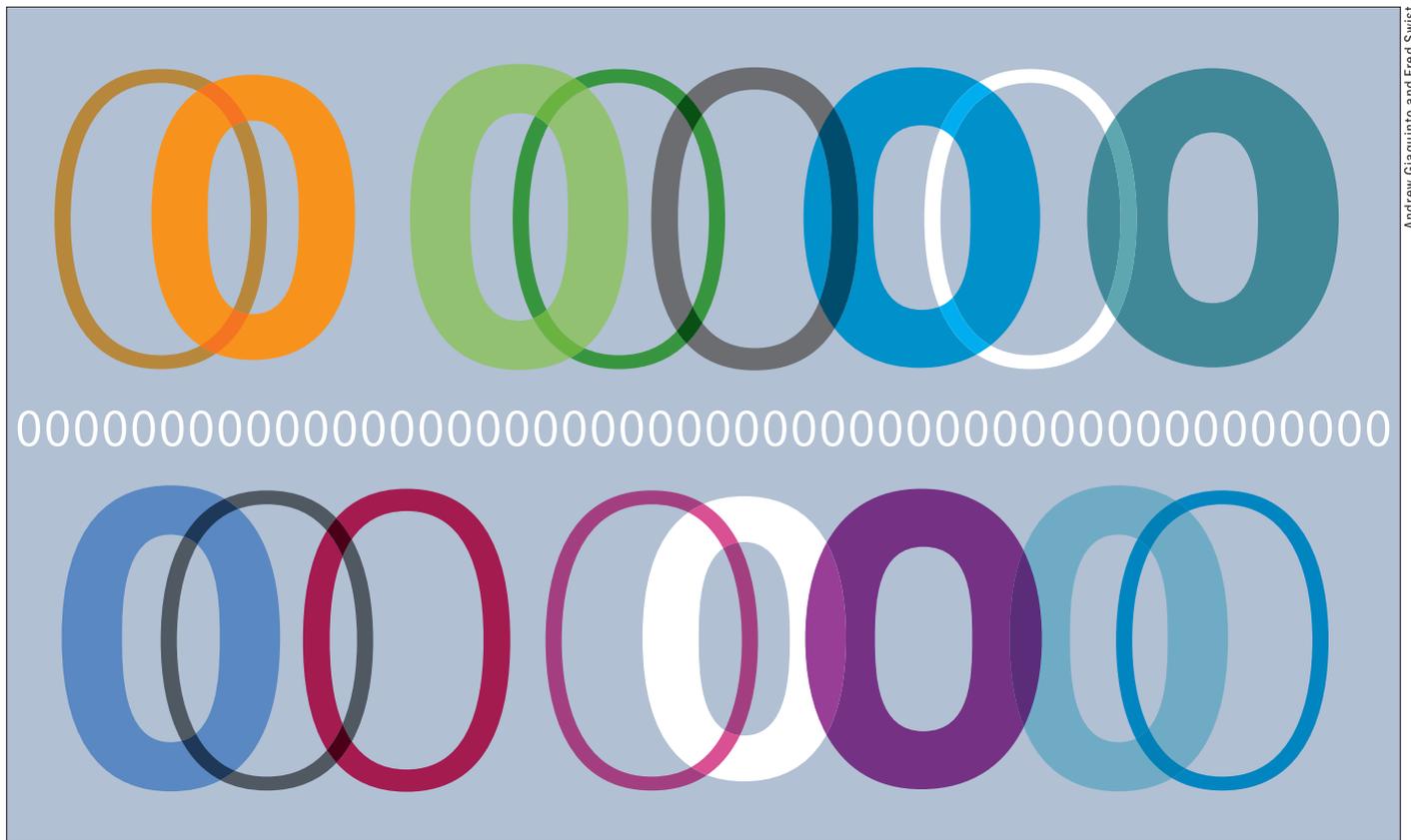
Two of those eyes belonged to Van Nieuwenhuizen, who grew up in the Netherlands and, after getting an extended Master's degree in mathematics, began studying theoretical physics in the mid-1960s under future Nobel laureate Martinus Veltman at Utrecht University. Veltman liked calculating – he had written a computer program, called SCHOONSCHIP, which was one of the first to do algebraic manipulations, and used it to calculate Feynman diagrams; he also tackled the renormalization of gauge theories with another student, Gerard 't Hooft. (Veltman and 't Hooft later shared the 1999 Nobel Prize for Physics.)

Van Nieuwenhuizen liked calculating too – as a student at Utrecht he had even organized seminars to work through problems with others. "But the attitude at the time in Europe was not calculating, only concepts and talking," he recalls. "I always felt a bit ill at ease with that." Such half-philosophies were not for him. "My taste is to have a very elegant, good, nice concept, but also hard evidence in calculations. If you all the time keep doing it, you become technically confident that what you do makes sense, and you're able to relate different areas."

His physics thesis was on radiative corrections to muon processes – the subtle effects of virtual particles, such as photons and electrons, that never appear in an experimental detector but nonetheless modify observed properties of a quantum process – and he continued with similar calculations during postdocs at CERN near Geneva and the University of Paris-Sud at Orsay. In 1973 he crossed the Atlantic to work with theorists Stanley Deser and Marcus Grisaru at Brandeis, where he did loop calculations in quantum gravity.

In the early 1970s quantum field theorists found that the infinities that appeared in their calculations would often disappear if every particle happened to be accompanied by a partner with a spin that differed by half-multiples of $h/2\pi$, where h is Planck's constant. Plunging boldly forward as only theoretical physicists do, they postulated a universal "supersymmetry" between fermions and bosons, and vice-versa, and happily investigated the consequences. But could supersymmetry be applied to gravity? And, if so, what would the theory look like? After discussing the idea over coffee, Van Nieuwenhuizen and Freedman, who had first met at a physics school in Paris, took up the problem, with the help of their friend Sergio Ferrara, who worked at CERN.

The trio wrote down the theory of a spin-2 particle – the graviton – with a spin-3/2 field as its supersymmetric partner. Such a field, which is not part of the Standard Model of particle physics, had been included in earlier supergravity work of 1975 by Pran Nath, Richard Arnowitt and Bruno Zumino, although it was not clear that the "superspace field" necessarily constituted a physical particle. The supersymmetry was local, holding at every point of space–time. So to see if the theory made sense, Van Nieuwenhuizen, Freedman and Ferrara did what physicists have been doing since the time of Euler – applied the principle of least action to the Lagrangian function to see if it changed under a local supersymmetry transformation. An action that did not change under suitable transformation laws (one that is "stationary", to use the jargon) would indicate a theory that was viable and supersymmetric.

In classical mechanics, the Lagrangian is simply the difference between a system's kinetic and potential energy. But the Lagrangian used by the three

In search of nothing
The crux of Peter van Nieuwenhuizen's work on supergravity was a computer program that would spit out only zeros if the theory was valid.

theorists was a much wilder beast – an unruly mix of metric tensors and Dirac spinors with indices galore, integrated over all of space–time. Specifically, the Lagrangian was the sum of the Lagrangian for general relativity plus that of Rarita–Schwinger, the latter being from William Rarita and Julian Schwinger, who in 1941 had developed a relativistic field equation of higher spin fermions, conjecturing that the then-undetected neutrinos of beta decay had spin-3/2 instead of spin-1/2 (see box on p36). And if that sounds complicated, well it is.

Einstein's Lagrangian for gravity is usually written in terms of the metric tensor – the function that specifies the distance between any two points in space–time. To make the local properties of their theory more apparent, the trio chose to describe gravity in a different but equivalent way first introduced by Hermann Weyl in 1929, in terms of objects called "vierbeins" and spin connections. The former, from the German words *vier* ("four") and *Bein* ("leg"), are a bit like the square root of the metric tensor in that their vector product in flat Minkowski space gives the metric tensor. They make Lorentz invariance – special relativity's requirement that all inertial frames of reference are equivalent – manifest at the local level, in other words near any point inhabited by an observer and their laboratory.
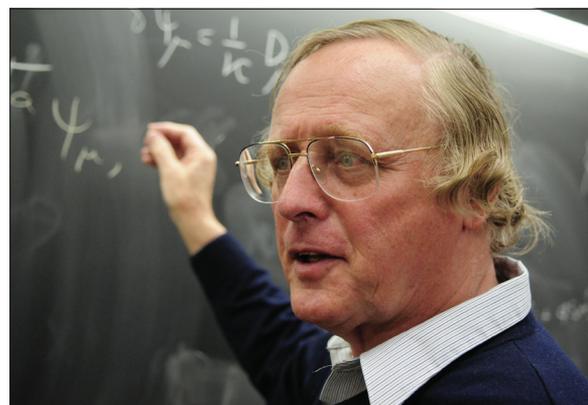
Mathematically, Van Nieuwenhuizen and Freedman then allowed their action to vary, before setting out to check whether that variation vanished. If it did, their theory would be valid – they would have constructed a field theory that combined general relativity with supersymmetry, at every point of space–time, and a reasonable candidate for a theory of quantum gravity. If it did not vanish, the theory was dust.

Fortunately, they liked to calculate.

Grinding it out

And calculate they did. Van Nieuwenhuizen and Freedman spent 12 hours a day together almost every day for at least half a year, evenings and weekends as well, together in front of a blackboard, transferring their results to notebooks when they found something good. Ferrara, offering moral support from CERN, was consulted by phone when the need arose (this being in the days before e-mail).

The variation of the gravitational part of the action was well known from Einstein's theory, and led to recognizable terms involving 4D tensors that described the underlying space–time. The difficult part was investigating how the spin-3/2 fermion interacted with the spin-2 boson under their supersymmetry, at every point in space–time. That required making intelligent trial guesses for how the gravitino spinor field, vierbeins and metric tensor would transform

A taste for calculation Peter van Nieuwenhuizen at Stony Brook.

under the supersymmetric transformation, and then grinding through the calculations. Van Nieuwenhuizen and Freedman calculated terms in order of their number of quantum field operators; the linear term, with one such operator, vanished after a "heartwarming" cancellation. When the next-highest-order terms unfortunately failed to vanish, they modified their transformation laws, an approach called the Noether method after the German mathematician Emmy Noether, whose work is now central to modern theoretical physics. Eventually, after some truly heroic tensor and spinor algebra, they found that a variation of the Rarita–Schwinger term produced a Ricci tensor, which wonderfully cancelled a Ricci tensor from a purely gravitational part of the calculation.
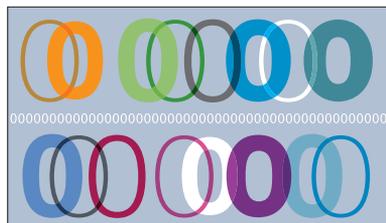
"It was such a miraculous, beautiful thing that we knew we were on the right track," recalls Van Nieuwenhuizen. Nor was it the only time that a tangle of mathematical objects surprised them by its simplification.

With even more work they showed that their particular choices for the Lagrangian function and transformation laws gave an action with a variation that vanished except for one particularly nasty term: the highest-order, "quintic" term that contains five multiplications of the spinor fields. It was given by:

$$t^{abcdefgh}(\psi_a^\dagger \sigma_b \psi_c)(\psi_d^\dagger \sigma_e \psi_f)(\varepsilon^\dagger \sigma_g \psi_h)$$

where ψ is the spinor field of the gravitino, a quantum field that is an operator at every point of space–time, σ represents Pauli spin matrices, ε is a spinor field representing the arbitrary supersymmetry parameter, while the cross superscript denotes Hermitian conjugation, and t is a multidimensional tensor of rank eight, with 4^8 (or 65 536) terms, each an integer.

In the quintic term all the 65 536 individual terms are added together and Van Nieuwenhuizen and Freedman knew that many of these terms were trivially or obviously zero, and that many were simply related to one another by symmetries. But they were still left with about 2000 terms sprung from the guts of the Pauli spin matrices. If they could show that all these terms vanished (or, with much less likelihood, that their sum did), the variation of their action would vanish and their theory would be valid. But if even one term failed to vanish, supergravity, as they constructed it, would not exist.

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They wrote up their progress, noting the hangnail left by the unevaluated quintic term, in a paper entitled "Progress toward a theory of supergravity". They then focused on evaluating the quintic term, and here the SCHOONSCHIP program came in handy. Van Nieuwenhuizen adapted it to calculate all of the pieces making up the quintic term, being sure to use every simplification trick he and Freedman could find because they were anxious about using then-expensive computer time. (In the end it came to about $50.)

An epic night

Late one night in the spring of 1976, Van Nieuwenhuizen was in the Stony Brook computer room, ready to run the program over a dial-up modem connection to nearby Brookhaven National Laboratory. It was 2 a.m. when he started the last run of their program – the decisive version that, they knew, was honed and ready. It was make-or-break time when Van Nieuwenhuizen submitted the run command over the phone line.

After about three minutes the results for the components of $t^{abcdefgh}$ started to come back. One zero after another appeared on his printer. A colleague also working late in the small room became intrigued when Van Nieuwenhuizen explained what he was doing. The first few hundred zeros were no big deal, Van Nieuwenhuizen told him, since those were clearly expected to be zero.

More zeros spooled out of the printer. Just one non-zero and their entire effort would fail. Still more – nothing but zeros. Tension grew, and Van Nieuwenhuizen says he started to make "strange noises". More zeros, and still more, all the way until the program terminated and the printer went still. Nothing but a couple of thousand zeros had spooled out of the printer. The quintic term had vanished. Supergravity existed.

Rather than feeling elated at the moment of victory – at the triumph of months of hard labour – Van Nieuwenhuizen says he was depressed, though he still cannot explain why. He called Freedman, who was in a hotel room in Chicago after a day at a conference. Freedman, too, was exhausted, and said little more than "Oh, that's wonderful." Van Nieuwenhuizen went home, he says, and went to sleep, and was depressed for days, perhaps not unlike postnatal depression, he thinks now.

They added a note to their paper (and an asterisk to the title), which appeared to great acclaim in June 1976 (*Phys. Rev. D* **13** 3214). A few weeks later two other theorists – Deser and Zumino – found a simpler but equivalent formulation of supergravity, as physicists often do after a brute-force method first discovers a result. (In fact, although the Zumino and Deser paper was submitted second, it was published first, in *Physics Letters B*, a week before Freedman, Van Nieuwenhuizen and Ferrara's paper came out in *Physical Review D*.)

Boom times

Two months later Van Nieuwenhuizen and Freedman published another paper exploring the landscape of their new theory (1976 *Phys. Rev. D* **14** 912), and the idea boomed as many other young theorists dived into the new world of supergravity.

It was a heady time, according to Van Nieuwenhuizen, and for students as well – there were more exciting and doable problems than people, he wrote. One notable theorist and future Nobel laureate later told him that he tried then to enter the supergravity field, but could not keep up with the dispiriting stream of papers that poured into his office. That youthful dominance did, however, create a problem, which was not understood by physicists outside the field. Because so few older researchers were involved in supergravity, young people were often not recognized when it was time for faculty positions and promotions.

The original theory is now called "pure" supergravity, and the spin-3/2 fermion that mediates supergravity interactions acquired the delightful name "gravitino". However, a spin-3/2 fundamental particle has never been detected experimentally, nor has any type of supersymmetry been found between fundamental particles.
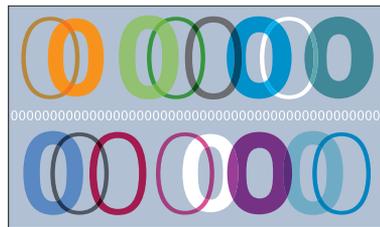
More zeros spooled out of the printer. Just one non-zero and their entire effort would fail

In a 1981 article on supergravity in *Physics Reports* (**68** 189), which CERN later listed as one of the 20 most referenced publications of the 1980s, Van Nieuwenhuizen wrote "The discovery of an elementary spin-3/2 particle in the laboratory would be a triumph for supergravity because the only consistent field theory for interacting spin-3/2 fields is supergravity. The remarkable thing is that a gauge symmetry between bosons and fermions can only be implemented in field theory if space–time is curved and hence if gravity is present."

Genes of string theory

Supergravity ultimately did not live up to its many hopes. It was very difficult to get the Standard Model out of even $N = 8$ supergravity, and it was never demonstrated to be renormalizable – that is, that its predictions could be rendered finite, as can those of quantum electrodynamics, quantum chromodynamics (the theory of the strong force) and calculations of weak-force interactions. But neither has it been shown that it is not renormalizable.

In fact, $N = 8$ supergravity is once again a hot topic. This "maximally supersymmetric" extension of Einstein's theory (that is, the version with the most supersymmetry transformations allowed for the theory to be self-consistent, with eight gravitinos, some of which can acquire mass via a super-Higgs effect) was first constructed by Eugène Cremmer and Bernard Julia back in 1979, by reducing its 11D version to four space–time dimensions. Although the theory appeared doomed because its short-distance behaviour seemed impossibly difficult to discern, in recent years truly gargantuan calculations by a team led by Zvi Bern at the University of California, Los Ange-

Where the action is

In the 16th century scientists such as Leonhard Euler, Pierre-Louis Moreau de Maupertuis and Gottfried Leibniz developed an alternative approach to mechanics than was put forth by Isaac Newton in his book *Principia Mathematica* of 1687. Central to their description was a quantity called the "action" – a function that could be calculated for any dynamical system. The path the system follows through space and time is that which keeps the action stationary – that is, which does not change the action, to first order.

The action of a system, between an initial and a final point, is the integral over time of another function, called the Lagrangian. In a classical system, such as a ball being thrown, it equals *T−V*, where *T* is the system's kinetic energy and *V* its potential energy. It will depend on the masses in the system, their spatial coordinates, their velocities and time. Given the Lagrangian, one can vary the action via the calculus of variation and deduce the path taken by the system, which will be that with the smallest possible value of the action – the path being a parabola for a ball. This is the principle of least action.

Einstein's general theory of relativity can be cast in terms of a Lagrangian and the principle of least action, and the principle has become central to quantum field theories as well. For example, Richard Feynman's rules for calculating the interactions of fundamental particles can be read off directly from the appropriate Lagrangian.

(The trick, of course, is finding the right Lagrangian.) In this way, Daniel Freedman, Peter van Nieuwenhuizen and Sergio Ferrara attempted to construct a theory of supergravity with the action, *I*, of general relativity (the spin-2 graviton) and that of a spin-3/2 particle.

It is a horrendous beast:

$$I = \int d^4 x (\mathfrak{L}_2 + \mathfrak{L}_{3/2})$$
$$= \int d^4 x \left[\tfrac{1}{4}\kappa^{-2}\sqrt{-g}\, R - \tfrac{1}{2}\varepsilon^{\lambda\rho\mu\nu}\, \overline{\psi}_\lambda(x)\gamma_5\gamma_\mu D_\nu \psi_\rho(x) \right]$$

The spin-3/2 Lagrangian, $\mathfrak{L}_{3/2}$, derives from work done in 1941 by William Rarita and Julian Schwinger, which built on the well-established formalism of Paul Dirac that so successfully described relativistic, quantum spin-1/2 particles such as the electron and positron. $\mathfrak{L}_2$ is the spin-2 Lagrangian and the other terms are spelled out in Van Nieuwenhuizen's papers

To vary the action, Freedman and his two colleagues wrote down supersymmetric transformation laws for the metric tensor, ψ, and the gauge fields, and calculated, calculated and calculated some more. At each step in the calculation, the transformation laws were modified or augmented to achieve an action with a variation that vanished. When it finally did, the trio knew that supergravity existed.

les, have used new mathematical techniques to show that certain versions of supergravity are, surprisingly, finite for small-distance scattering at up to four internal loops of virtual particles, such as $N = 8$ supergravity in four and five space–time dimensions. Even more magic may lie inside the theory.

Supergravity is in fact the low-energy limit of string theory and it gave theoretical physics a hefty boost along the road towards superstrings, which has become the prevailing effort to unify physics. "Supergravity turns out to be a tiny piece of string theory," says theorist Joseph Polchinski of the Kavli Institute for Theoretical Physics in Santa Barbara, California, "but this tiny piece reveals more important features that are not at all obvious from other points of view." These include the dualities – direct analogies between subjects like electricity and magnetism, or the conjectured link between string theories with gravity to quantum field theories without gravity – that are essential to any understanding of quantum theory. "Indeed, what we now call 'string theory' gets many of its genes from supergravity."

would imply supergravity as well.

Supergravity makes predictions, but unknowns cloud the picture. "You can always just push up the supersymmetry-breaking scale and make supergravity at low energies look more and more indistinguishable from the Standard Model," says Peter Woit, a mathematical physicist at Columbia University who has often been critical of super-theories. "There are distinctive features of such theories, for example the gravitino, and if you saw such a thing, you could say this was confirmation of supergravity. But not seeing such a thing doesn't tell you that supergravity in general is not there."

Time of one's life
Freedman went to the Massachusetts Institute of Technology in 1980, where he remains on the faculty. As for Van Nieuwenhuizen, he stayed at Stony Brook, where from 1999 to 2002 he was director of the C N Yang Institute for Theoretical Physics. Now 73, he is still there as faculty, having published more than 330 scientific papers and supervised 16 doctoral students.

He, Freedman and Ferrara were awarded the 1993 Dirac Medal by the International Centre for Theoretical Physics for their discovery of supergravity's existence and subsequent contributions. In 2006 the trio also received the prestigious Dannie Heineman Prize for Mathematical Physics, administered jointly by the American Physical Society and the American Institute of Physics. But for all Van Nieuwenhuizen's achievements, the many hours spent constructing supergravity and showing it existed was "definitely the best time of my life", he says. "Looking back on that time, it's fantastic. If you do something where every day is interesting, hard work, things going wrong, all the time cliffhangers…well, it's the most beautiful time you can have."
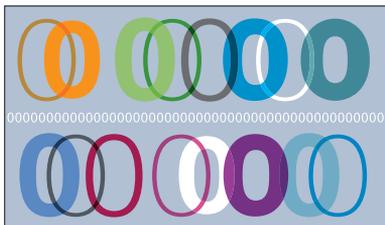
The discovery of an elementary spin-3/2 particle would be a triumph for supergravity

Supergravity was based on a symmetry principle – a symmetry between bosonic and fermionic fields. That symmetry can only be implemented if space–time is curved – that is, if gravity is present. Were supersymmetry to be found at, say, the Large Hadron Collider at CERN, a large number of models