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Why do we need supersymmetry?

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The word supersymmetry came to me for the first time in 1980 when I was the third-year student at the Physics Department of Tomsk State University in Western Siberia, in the former Soviet Union. Unlike the physics students in Moscow (not to mention those in the West), we were quite isolated from the Big Science, since there was no single laboratory to be related with either experimental or theoretical high energy physics in Tomsk and, of course, there were no local traditions at all. The first breakthrough in Tomsk came a few years earlier, with the opening of the quantum field theory group under the supervision of Prof. V. Bagrov, an expert in exact classical solutions to the Dirac equation in external electromagnetic fields, who was lucky to spent some time at the Physics Department of Moscow State University. Learning about the Dirac equation from the lectures of Prof. V. Bagrov appeared to be my first step towards supersymmetry.

In 1980 Prof. E. Fradkin from the Lebedev Physical Institute in Moscow asked Prof. V. Bagrov to send some of the best physics students from Tomsk to Moscow, for doing research under his supervision. The only condition of Prof. E. Fradkin was that the students should be maximally 20 years old, since, otherwise, it would be too late for them to study theoretical physics (!) I was amongst these students. Of course, we were not taken seriously in Moscow, and all of us were very embarrassed there, since we didn't understand a word during the first meeting with Prof. E. Fradkin. One should also mention that the way of dealing with students (at least with us) was very cruel in Moscow: our senior supervisors expected from us to know everything, from quantization of non-abelian field theories until N=8 supergravity, as the pre-requisite for any serious discussion, which was, of course, unfair. From our first trip to Moscow we just learned a few foreign words, with 'supersymmetry' being one of them. The first tough lesson in Moscow gave us the first motivation to learn supersymmetry in Tomsk, simply because there was no other challenging message around. Perhaps, it is hard to imagine now, what it was to learn supersymmetry in Siberia, in the absense of regular western literature and world-wide-web (not to mention a personal computer). We were getting the scientific papers privately from the capital, which implied regular travel about 3100 km from Tomsk to Moscow and back, spending a lot of time in the Moscow libraries, and copying hundreds of pages there (no xerox machines were available in Tomsk).

Fortunately, there were a few senior people in Tomsk at that time, who helped us with our education in quantum field theory: for example, Prof. I. Tyutin (T in the BRST) from the Lebedev Institute. We were suddenly offered a plenty of lectures and seminars about group theory, field theory, supersymmetry and quantization (everything on the top of regular courses at Tomsk University), much earlier (and, sometimes, instead) of many standard courses in physics. Because of this background, when I became a graduate student and again came to the Lebedev Institute in Moscow, I had no doubt that supersymmetry is the only thing worthy to be studied.

Now, after 20 years, I ask myself again, (i) how should we classify the subject of supersymmetry, (ii) why do we need supersymmetry, and (iii) what is the future of supersymmetry ? I would like to offer my own, very personal view on these matters.

As is well known, the first papers about supersymmetry appeared in the early seventies, in the former Soviet Union. Drs. Yu. Gol'fand and E. Lichtman from the Lebedev Physical Institute in Moscow found a supersymmetric extension of the Poincaré algebra for the first time, whereas Prof. D. Volkov and Dr. V. Akulov from the Phys.-Technical Institute in Char'kov (Ukraine) discovered a field-theoretical model with spontaneousy broken supersymetry. However, these fundamental discoveries were not immediately recognized or appreciated by the very strong community of theoretical physicists in the former Soviet Union and, especially, in and around Moscow. Only after the fundamental papers of Prof. B. Zumino and Prof. J. Wess from CERN, who pioneered the representation theory of supersymmetry in field theory, the explosion of papers devoted to supersymmetry really began. The natural question arises why the discovery of supersymmetry was largely ignored in the former Soviet Union until the Wess-Zumino contributions? I believe that the reason was two-fold. On the one side, the early inventors of supersymmetry apparently didn't appreciate themselves the true meaning of their discoveries. For instance, the Gol'fand-Lichtman paper was merely devoted to presenting a new super-algebra, whereas the Akulov-Volkov investigation was motivated by the search for a non-linear Lagrangian describing neutrino as Goldstone fermion, without looking for linear realizations of supersymmetry and its relation to spacetime symmetries. On the other side, the message came from the researchers who didn't belong to the top brass of the (highly hierarchical) scientific establishment in Moscow. Being a student at the Lebedev Institute in Moscow, I got an impression that, for example, Yu. Gol'fand was often treated as a 'crazy guy' amongst his colleagues. I attended two of his seminars, and I can now acknowledge this opinion. Perhaps, one ought to be crazy in order to generate a crazy idea which is crazy enough to be right! On the contrary, the Theory Department of CERN was very quick in recognizing and appreciating the fundamenetal meaning of supersymmetry as the unifying symmetry between bosons and fermions (i.e. the right place, the right people and the right time).

The fact that supersymmetry was never experimentally observed or confirmed does not apparently bother most theoretical physicists at all. After all, the theoretical fundament of supersymmetry is much broader and solider than that of many other modern theoretical constructions. As a result, the need to motivate supersymmetry itself totally disappeared from the current literature dealing with supersymmetry. Theoretical consistency and experts opinion have long substituted the objective experimental criteria in the modern theoretical high energy physics, including supersymmetry. Moreover, it is sometimes very difficult, if not possible, to distinguish between proved statements and conjectures either in the current literature or in the hep-th archive. From this perspective, supersymmetry can be considered as a kind of art, or as part of mathematics. I would, nevertheless, refrain from identifying supersymmetry with the intellectual entertainment for qualified scientists.

Supersymmetry is not only the part of theory. It also creates jobs and attracts money. Any new (bosonic) field theory entering the theory market may be supersymmetrized; this gives the unlimited source of motivation for writing new theoretical papers and Ph.D. Theseses, as well as demanding new post-doc positions from the funding agencies. Once the abstract theory language of supersymmerty had become available in physical terms for experimental physicists, the search for supersymmetry turned into one of the main topics in their agenda, with all its cosequences to be related with a construction of new expensive experimental devices like LHC. Hence, supersymmetry is the business enterprise also.

Yet another unusual view on supersymmetry is provided by evaluating the problems in supersymmetry as the challenge for supersymmetry experts. For example, once a bosonic theory is supersymmetrized once, it may be supersymmetrized twice, etc. with the increasing level of complexity. One may also go in the opposite direction: once a model with partial (1/2) supersymmetry breaking is found, one may try to get other patterns with 1/4, 1/8 or even 3/16 of supersymmetry breaking, which are definitely much harder to construct. The challenge results in a competition, the competition gives rise to winners and losers, the winners get recognition and prices. Hence, it is also possible to identify supersymmetry with a kind of sport too.

If something can be simultaneously interpreted as science, business, art and sport, it is definitely the important subject that is going to stay with us forever. In the rest of this paper I would like to concentrate on the functional role of supersymmetry in modern theoretical high-energy physics.

The standard motivation for supersymmetry is based on its interpretation as the unification symmetry between the fundamental bosonic and fermionic degrees of freedom. Supersymmetry is also known to be the only non-trivial way of unifying the spacetime symmetries and the internal symmetries. Being the 'square root' of spacetime, local supersymmerty immediately implies gravity. This motivation was put forward in the early days of supersymmetry and supergravity towards a formulation of the unified field theory of all fundamental physical interactions, including gravity. The hope was that the maximal supersymmetry (realized in N=8 supergravity) could automatically care of the problems beyond the Standard Model. This didn't happen, and it gives us the lesson that a relation between supersymmetry and particle physics is less straightforward as it seemed in the beginning of the supersymmetry era.

The development of supersymmetry is to be compared with the (apparently unrelated) development of the dual models (now known as string theory), before their unification proposed by Prof. J. Schwarz from Caltech and his collaborators. In fact, the fermionic dual models already had (what is now called) world-sheet supersymmetry, so that it was not very surprising that the Wess-Zumino work appeared to be a catalyzator for a discovery of spacetime supersymmetry in the fermionic dual models (now called superstring theory). String theory also gives us another lesson that the naive increase in the amount of supersymmetry is not always productive: for example, the world-sheet supersymmetry of the NSR string model was abandomed in favor of spacetime supersymmetry, the N=2 world-sheet supersymmetric strings are inconsistent at the one-loop (string) level, while the strings with N=4 world-sheet supersymmetry do not have the spacetime interpretation at all (their critical dimension is negative or zero).

A deeper consequence of supersymmetry is cancellation amongst Feynman graphs (and their ultra-violet divergences) between bosonic and fermionic contributions. This is not only crucial for particle physics (e.g. as regards the hierarchy problem), but is of paramount importance for getting solutions to quantum gauge theories and strings. As is well-known, the description of the non-abelian quantum gauge theories in terms of the fundamental (Yang-Mills) variables becomes invalid below some energy scale, due to singularities in quantum perturbation theory. As a result, the strong coupling description in these theories (like QCD) is out of reach. The main physical obstruction is the complicated vacuum structure of the bosonic gauge theories, which results in the (theoretically) uncontrollable screening of charges, etc. Supersymmetry causes the cancellation between screening and anti-screening of the bosonic and (very specific) fermionic contributions, which greatly simplifies the low-energy behaviour in the supersymmetric quantum gauge field theories. If the amount of supersymmetry is enough (as it happens to be the case in the N=2 supersymmetric quantum gauge field theories in four spacetime dimensions), the exact low-energy solutions are possible, as was demonstrated in the seminal papers of Prof. N. Seiberg and Prof. E. Witten from Princeton in 1994. Without supersymmetry, instanton contributions are plagued by infra-red divergences.

We can, therefore, conclude that there is the conflict between the 'realistic' (phenomenological and nonsupersymmetric) field theories, which are best exemplified by the non-solvable Standard Model, and the supersymmetric gauge theories which may be solvable but are certainly non-realistic. This conflict reminds me the conflict between the (unrealistic) Yang-Mills theories and their (realistic) spontaneously broken counterparts, which is resolved by the Higgs effect. One expects that the ultimate marriage of supersymmetry and phenomenology can only happen after a super-Higgs effect of spontaneous supersymmetry breaking. Spontaneous breaking of any symmetry allows us to keep control over the effective action. Spontaneous breaking of supersymmetry naturally implies the existence of the corresponding Goldstone action whose structure is uniquely determined by the broken supersymmetry. This mechanism is realized in the D-branes and M-theory, which has the promise to be the ultimate unified theory of Nature. Supersymmetry then plays the role of the universal regulator which puts strong coupling under control and eliminates unphysical degrees of freedom (like a tachyon). This may imply an even grater role of supersymmetry in making the supersymmetric non-abelian quantum gauge field theories and superstring theory to be well defined beyond quantum perturbation theory.

Yet another example in support of the last conjecture is provided by the AdS/CFT correspondence. As is widely believed, the QCD confinement is a non-perturbative solution to a four-dimensional quantum $SU(N_{\rm c})$ gauge field theory with $N_{\rm c} = 3$. A formal proof of the colour confinement amounts to a derivation of the area law for a Wilson loop $W[C]$. The so-called 'string' Ansatz

$$W[C] \sim \int_{\substack{\text{surfaces } \Sigma, \\ \partial\Sigma = C}} \exp\left(-S_{\rm string}\right)$$

clearly shows that the effective degrees of freedom (or collective coordinates) in QCD at strong coupling (in the infrared) are the (QCD) strings whose worldsheets are given by the surfaces Σ, and whose dynamics is governed by a string action S_{string}. The fundamental (Schwinger-Dyson) equations of QCD can be put into the equivalent form of the (infinite chain) equations for the Wilson loop. This chain of loop equations drastically simplifies at large number of colours N_c to a single closed equation known as the Makeenko-Migdal (MM) loop equation. Only planar Feynman graphs survive in this limit. Unfortunately, such approach was never successful in the past, largely because it was unable to take into account quantum renormalization and fix the relevant string action S_{string}. The first problem may be circumvented via replacing QCD by the N=4 Supersymmetric Yang-Mills (SYM) theory that is known to be UV-finite and conformally invariant. As was conjectured by Maldacena, the N=4 SYM theory is dual to the IIB superstring theory in the $\text{AdS}_5 \times S^5$ background. The Maldacena conjecture can therefore be interpreted as the particular Ansatz for the string action, $S_{\text{string}} = S_{\text{IIB}/\text{AdS}_5 \times S^5}$, as regards a solution to the N=4 supersymmetric (MM) loop equation, provided that spacetime is identified with the boundary of the Anti-de-Sitter space AdS_5. This CFT/AdS correspondence gives rise to simple mechanisms for simulating confinement and generating the mass gap after breaking the conformal invariance and supersymmetry in the 'finite-temperature' versions of Anti-de Sitter spaces, as was demonstrated by Prof. E. Witten in 1998. These recent results lend further support for the role of supersymmetry as the universal regulator in quantum field theory and strings, which seems to be indispensable for their non-perturbative definition.

Anyway, supersymmetry is fun, and it is certainly going to be with us in any forseeable future.

The number of relevant papers about supersymmetry is very large, while they can be easily identified when using the standard databases in theoretical high-energy physics, available in internet. So I decided to skip all references.

The idea to write down these notes came to me in response to the question put in the title that was raised by a student during my lecture.