Unravelling Nature's Elementary Building Blocks

Challenges of Big Science*

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Summary

Unprecedented international efforts have resulted into amazing insights in the world of subatomic particles and the forces that control their dynamical behavior. This required large and delicate constructions to obtain experimental information, as well as advanced and ingenious mathematical methods to formulate our theories. Yet there is still a vast unknown territory. We do not know how to describe the way matter interacts with gravity at the very tiniest distance scales. At present we can only speculate about nature's deepest secrets.

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1. Introduction. The quantized fields

Once upon a time, there was a point. It was the only thing that existed. Even the fabric of space and time did not exist. The point is modern science's version of creation.

Then that point exploded. It was an explosion of a kind that would never happen again. It was unique. It was the very beginning of the Universe, our universe. The explosion took an unimaginable short amount of time, some 10^{-44} seconds only. There were no witnesses. The only things we know about it is what could be reconstructed afterwards. It wasn't any material substance that exploded. It was space and time itself. In the explosion, space was created. Originally, there were only few particles in this space, but their numbers would very rapidly increase. During the first tiniest fractions of a second, the conditions were so extreme that we can only guess what kind of fundamental laws were governing their behavior, but then the temperatures lowered sufficiently so that we know exactly what happened next. Soon after the explosion, the universe managed to grow spectacularly, until our part of this universe, that is, the part that we can now study in our telescopes, was several centimeters across. This growth was spectacular, because the amount of time that had elapsed, some 10^{-35} seconds, would have allowed light to travel less than a tiny fraction of an atom's nucleus.

While the universe continued to expand, it also cooled rapidly. A fantastically large number of particles had grown out of the explosion. First quarks and leptonic particles emerged, then they started to form larger units, protons, neutrons, and primitive atoms. Only millions of years later, galaxies formed, and they produced stars and planets, heavier atoms and molecules. Our universe started to look like it is today.

Science of the twentieth century started with the discovery of two beautiful schemes exploited by nature to control the behavior of matter. One of these was called *special relativity*, and it tells us how to understand fast moving particles if we know what they look like when at rest. It was Albert Einstein who discovered in 1905 how the concept of motion can be seen to be relative, while the speed of light is nevertheless an absolute concept. Pure logic was all that was needed to draw some far-reaching conclusions. In particular, when particles move nearly as fast as light itself, some 300,000 km/sec, the geometric structure of space and time generates very peculiar features in them.

The other beautiful scheme that was discovered shortly after that, is more difficult to explain. It is called "quantum mechanics", and it dictates in detail the logical framework in which to describe very *tiny* particles, replacing the crude mechanical properties of heavy things called "classical mechanics". Quantum mechanics tells us that the notions of position and velocity of a particle have to be replaced by the mathematical equations for *waves*. The rules are again very precise, and the theory is extremely successful.

However, when particles move with velocities comparable to that of light, but are also so tiny that the laws of quantum mechanics must be applied, a problem was encountered: here we should have *both* quantum mechanics and special relativity at work. Combining these two very different paradigms into one turned out to be a sizeable exercise. The name of this new subject was easier to devise: we speak of "elementary particles physics", since it is the elementary subatomic particles that combine their light weight with speed. But another name is "high-energy physics", used particularly by experimentalists, who have to administer extreme amounts of energy to single particles in order to observe the specially interesting effects, or "quantum field theory" by theoreticians, since we now know what must be done to obtain a coherent and detailed theoretical description.

When quantum particles interact at high velocities, it is inevitable that new particles are created, and others disappear. This made the problem of combining quantum mechanics with special relativity rather complicated. It was not before the 1970's when a complete solution to this problem was uncovered. We found that all elementary particles must be viewed as the quantized energy packets of *fields*. These fields obey field equations, and it was these field equations that were easier to reconcile with the laws of quantum mechanics than the equations of motion of particles, whose numbers, after all, may be variable. It turned out that the value of a field at a space-time point $(\vec{x},\, t)$, will always be controlling the creation and the annihilation process of one particle, precisely at the point $\vec{x}$, and at time t.

But further information from experimental observations was needed. Experiments told us that particles are subject to different kinds of forces. One has:

— The electromagnetic force. It is characterized by Maxwell's equations, discovered in the 19^{th} century by J.C. Maxwell. The range of this force is infinite; electric and magnetic fields can stretch across interstellar space while the force is also felt at distance scales as tiny as that of the subatomic particles.

The solutions of these field equations can form waves that always propagate at the speed of light. Indeed, they were quickly recognized to describe light itself. After subjecting these fields to the laws of quantum mechanics, it was found that the energy quanta of these waves are to be identified as particles, the so-called photons. Another force is

— The strong force. The strong force dominates inside the nuclei of atoms, where it is the cause of a strong attraction between the constituents, thus providing the nuclei of a quite sturdy structure. This force was first thought to act only over short distances, but this picture had to be corrected. The strong force remains equally strong at large distances, so much so that particles that are directly sensitive to this strong force, such as the *quarks*, can never separate very far; they keep sticking together and this way they actually screen this force from the outside world. This phenomenon is called "permanent confinement".

The strong force however acts only in a particular, symmetric way. If one looks in the asymmetric directions, one discerns a third type of force,

— The weak force. This force is only noticeable in situations where the other forces have no effect, for instance, they cause transitions of particles into other types of particles. This force is actually not much weaker than electro-magnetism, but it looks weaker, because its *range* is truly short.

The structure of the field force lines is sketched in Fig. 1a), where the distance dependence is also shown (b). At small distances, all forces are inversely proportional to the distance squared. At large distances, the electro-magnetic forces continue to drop off like $1/r^2$, the weak force drops off exponentially, and the strong force tends to a constant instead of going to zero.

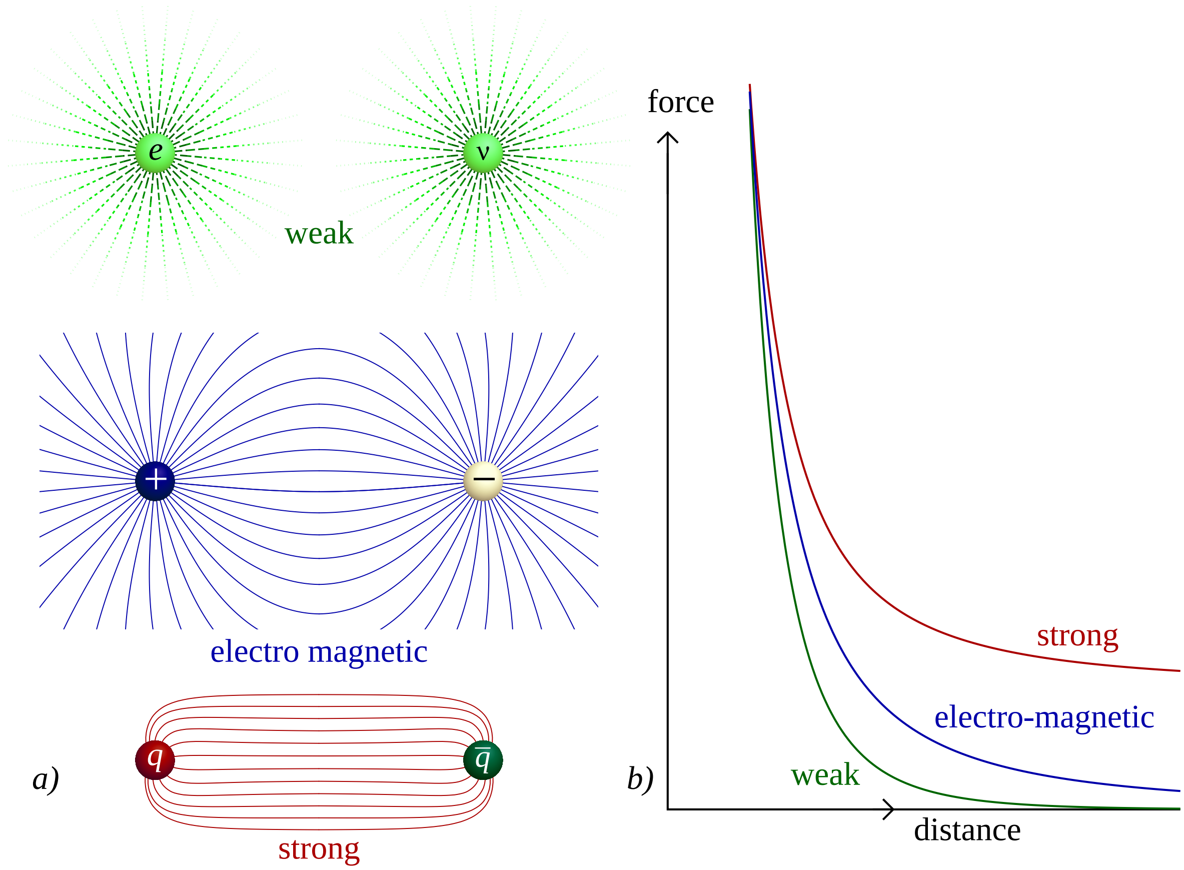

Figure 1: Forces can vary with distance in three fundamentally different ways. a) The force lines, b) Force depending on distance.

2. The Yang-Mills field

In 1954, for no particularly good reasons, C.N. Yang and his collaborator Robert Mills asked how one might imagine fields obeying more complicated equations than the Maxwell equations of the electric and magnetic fields. Starting from the same general principles, they discovered that one might have fields very similar to electric and magnetic fields, but where the fields not only subject the particles to forces, but also cause the particles to transmute into other particles. A proton, for instance, might turn into a neutron. A positive pion might turn into a neutral or a negative one.

At first sight, the equations seem to make a lot of sense, and applying our quantization scheme to these fields could lead to a description of very interesting sets of particles, the

"Yang-Mills gauge bosons". When, in a Yang-Mills field, a proton turns into a neutron, one unit of electric charge disappears. This, however, is readily accommodated for in the theory, since the Yang-Mills bosons may carry one unit of charge, and thus make up for the deficit.

Furthermore, the theory demands that all particles that interact with the Yang-Mills fields, form *multiplets*. The proton and the neutron form a doublet, the pions a triplet, and so on. The Yang-Mills bosons themselves also form a multiplet, being a triplet in the simplest case. Yang-Mills transitions can only occur within one multiplet: protons never turn into pions, since those form a multiplet that is different from the proton-neutron doublet.

However, not all seemed to be in order, when Yang and Mills first proposed their model. In particular, the Yang-Mills bosons obey equations that are so similar to the Maxwell equations, that the Yang-Mills gauge bosons are like photons, and they should move with the speed of light. Charged particles, however, are not allowed to move that fast; they are known to carry energy, hence inertia, and as such they must be limited to move slower. To realize this property, the equations had to be modified, but, when this was tried, contradictions started to build up. The difficulties were such that the Yang-Mills model was practically abandoned until the early 1970s.

But then, two new discoveries were made that could change everything. One was a mechanism called "spontaneous symmetry breaking". It required the existence of another kind of field, the so-called Higgs field. The Higgs field is very different from the other fields considered before. It is a field without any orientation (called a *scalar* field), but which does interact in a very special way with the Yang-Mills system, because it has various components: it is a Yang-Mills multiplet, and it disrupts "spontaneously" the internal symmetry of the Yang-Mills system. After the dust settles, not only the Yang-Mills gauge bosons now carry mass, but also one new, non-rotating particle emerges: the Higgs particle. By interacting with this particle, the entire theory gets much more structure, because the different members of one multiplet are now allowed to have slightly different properties. This way, a quite realistic and workable model was found for describing all observed properties of many particles.

The second discovery was that, if these rules for symmetry breaking were followed, field equations were obtained that allow for very detailed calculations. The peculiar quantum effects could be calculated with tremendous precision, at least in principle (in practice, this may become quite hard!). The theory was called 'renormalizable'.

3. The strong force

The above scheme worked particularly well for the *weak* forces. They all turned out to originate from a simple Yang-Mills field setting. But to understand the strong forces, more was needed. After various false starts, it was discovered that the strong force, too, can be ascribed to a Yang-Mills system. The particles sensitive to the strong force are the quarks, and they are now assumed to form a new kind of multiplets, on top and above the multiplet structures some of them already had in view of the weak force. The strong quark multiplets are triplets, and, in contrast to the weak case, the different members of a strong multiplet are assumed to be fundamentally indistinguishable. The three states a quark can be in are designated as their "color": red, green, or blue. Coloured states are either attached to other states with opposite colors (green-blue, violet or yellow), or to a pair of the other two colors, such that the entire combination has all its colors neutralized. Since only these color-neutral combinations can emerge as free particles, not attached to anything else, we say that our particle detectors are 'color-blind'.

Let us emphasize here that these features have nothing to do with ordinary color vision; at energies one billion times higher than that of colored light, we use the word 'color' as a metaphor.

A Yang-Mills field now couples to these 'color' charges, causing the attraction between opposite colors. However, since Yang-Mills gauge bosons themselves also carry color, the dynamics of this field is more complicated than in the case of electro-dynamics. There is also an important difference with the weak force: there is *no* Higgs field to generate any spontaneous symmetry breakdown. The full implications of such a theory were not fully appreciated until the early 1970s. The strong color field was understood to be a long-range field, but exactly why does it generate permanent quark confinement? How come that quarks cannot get detached, beating the binding force, just like electrically charged particles can get detached, by beating the electric force? This was the subject of the 2004 Nobel Prize in Physics. It was discovered that a strong color force can accumulate strength when color charges would tend to be separated. In contrast, this force attenuates when particles come very close together, a property named 'asymptotic freedom' ('asymptotic' here stands for the limit for asymptotically *small* distance scales)

It was furthermore discovered that, even though quarks cannot be isolated and detected, one can still test the theory very accurately. Quarks can be produced at very high energies via standard quantum field theoretical processes. Since they start out being very close together, they first travel along nearly straight lines, since the strong forces are then still weak. Then the strong forces build up, but instead of stopping the quarks altogether, the strong forces produce pairs of quarks and antiquarks between them, thus neutralizing the original colored quarks. This produces colorless physical particles such as pions, protons and neutrons. These particles continue to travel in the same direction, with the same energy, as the original quarks, and they can be detected. This way, one can reconstruct the paths of the original quarks, and test the theory. This theory, now called *Quantum Chromodynamics* (QCD), turned out to be highly successful, see Fig. 2.

4. The Standard Model

After the strong force fell into place, a more or less complete picture emerged of the various kinds of subatomic particles and the forces that act between them. The simplest Yang-Mills theory that can be used here, was originally regarded as an idealized *model*, whose predictions could be compared with the outcome of measurements on the particles known. With a few more technical additions, the complete model obtained this way, was

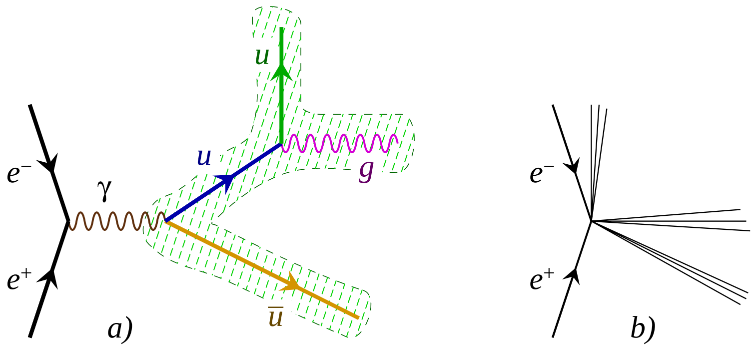

Figure 2: Jets in QCD. a) Diagram depicting the production of colored particles, b) The way this process is detected in a particle detector. The outgoing particles are predominantly protons, neutrons and pions.

called the *Standard Model*, see Fig. 3. It brought a surprise: this model accounts for all observed data so accurately, that, rather than just an "idealized" model, it can better be respected as a *theory*.

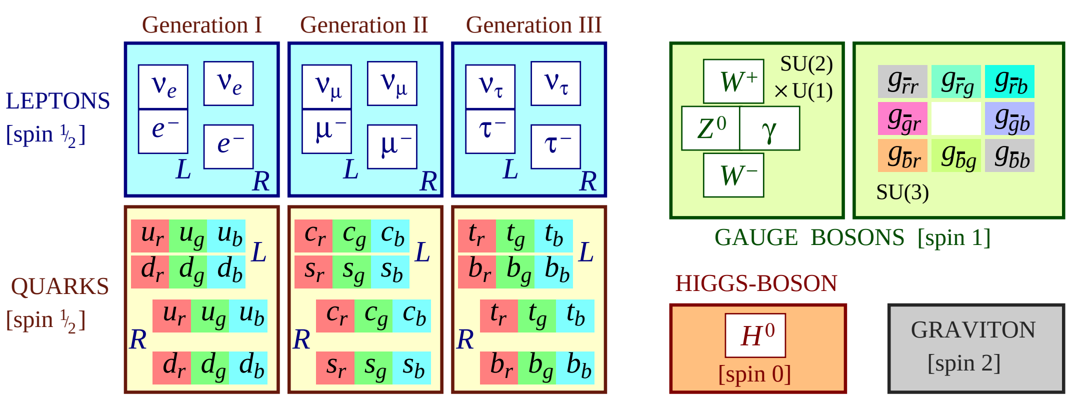

Figure 3: The Standard Model. The left-rotating quarks and leptons (indicated by an L), form weak Yang-Mills doublets, the right-rotating ones (R) are singlets.

Laboratories in which subatomic particles are investigated experimentally tend to be very large. The reason is that as much energy as is possible must be pumped into single particles, which are then allowed to collide. The tiniest structures are revealed if fast moving particles collide head-on, so beams of particles are generated, oriented in two opposite directions. The more energy particles in a beam have, the harder it is to deflect the beam. Usually, the two oppositely oriented beams move in large, circular tubes, and they are made to collide at several points along these circles. Since the particles are very small (they have a very tiny cross section), the beams are made as narrow as possible at the collision points, typically microns in diameter or even smaller.

To force the particles into circular orbits, and to control the other features of the beams, powerful magnets are needed, and to accelerate the particles one needs very strong electric fields. The biggest of these machines was the Large Electron-Positron (LEP) collider of CERN (Centre Européen de Recherche Nucléaire) near Genève, in a circular tunnel of

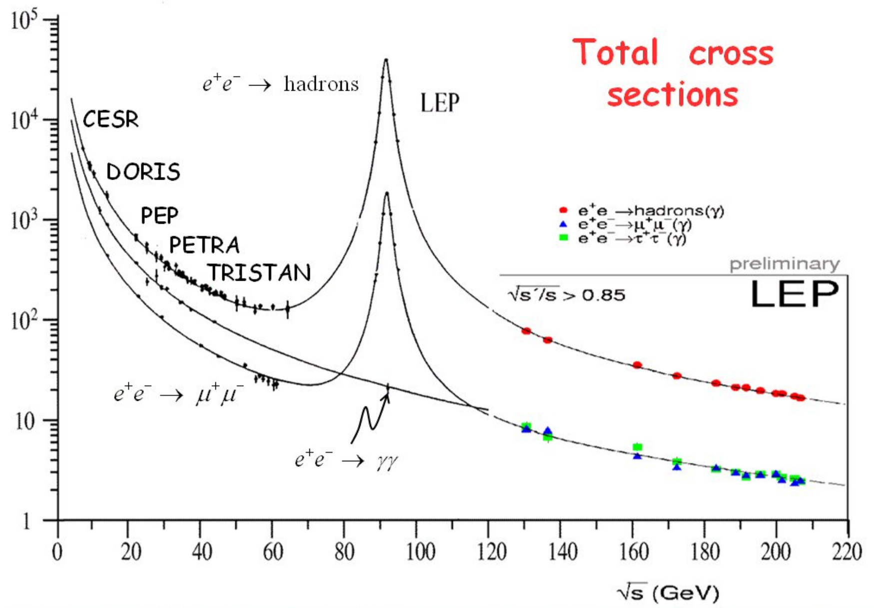

Figure 4: Various cross sections measured in the energy range 0 — 200 GeV.

more than 26 km circumference. Fig. 4 shows measurements made by several laboratories combined. The solid lines are the present Standard Model calculations. The part at the right was produced when LEP had been upgraded to reach 200 giga-electronVolt (GeV) per particle. It shows no deviations from the Standard Model predictions.

One piece of confirmation is still missing; this is the Higgs particles itself. Indirectly, the Higgs particle's presence is felt everywhere in the Standard Model calculations, and it is generally agreed that the experimental data suggest that there indeed is a Higgs particle with mass between 115 and about 200 GeV. Theoreticians cannot give more accurate predictions of this mass; indeed, it could be that several Higgs particles exist, with widely varying mass values. If we would remove the Higgs particle, the Standard Model would become much less precise and not match the observations so well.

LEP has now been dismantled, and the same tunnel is now used to house a new, more powerful accelerator called "Large Hadron Collader", LHC. With this machine, we should obtain moch more detailed information about the Higgs particle(s), and hopefully get a first glimpse of new ingredients that could well put the Standard Model on a higher level; many researchers expect new species of particles that would realize a symmetry that has been speculated about for decades: supersymmetry. Supersymmetry relates fermionic particles, such as the quarks and leptons, with bosonic ones, such as the Higgs and the gauge bosons, but it requires the existence of many new particle species that have not yet been found. LHC should be fully operational in 2007.

The Standard Model is the answer to the question posed in the first half of the 20$^{\text{th}}$ century: how do we formulate a theory to which both special relativity and quantum mechanics apply? Clever experimental techniques and new theoretical insights, realized across the globe, enabled us to discover this answer. The Standard Model describes all fundamental particles known to us at present. They obey universal laws of physics. The mathematical structure of the theory is such that exactly 26 fundamental "constants of nature" are needed to describe all interactions (including the gravitational force). 12 of these describe masses of particles, 4 are fundamental coupling strengths, and the remaining are so-called "mixing parameters", caused by interactions with the Higgs field. Some of these interactions are left-right asymmetric; particles and antiparticles behave differently from their mirror images. It may seem that 26 freely adjustable numbers is a lot to make the model conform all experimental data, but actually it is amazingly little. There are hundreds of different particle species and thousands of experiments that have been done; all of these are matched by the same set of 26 numbers.

5. Grand Unification

Yet we do know that the Standard Model is incomplete. There are several reasons for this. One of these is *naturalness.* The deeper we dig into the internal structures of our particles at the tiniest distance scales, the more need there appears to be for "fine tuning". This means that some of the 26 constants of Nature take values in this domain that look unnatural, as if someone has carefully tuned them so as to give the particles structures as seen at our present energy scales. To many researchers, this suggests that the Standard Model has a further underlying structure that we know nothing about, as yet.

A second reason to put question marks at the present shape of the Standard Model is that, even if it allows us to calculate its predictions vary accurately, there is an inherent limit to the precision possible, even if we had unlimited calculation powers. The model is imperfect from a mathematical point of view.

The most disconcerting imperfection, however, is the way the gravitational force has been taken into account. Gravity has been incorporated into relativity theory in a beautiful way by Albert Einstein in 1915, resulting in what became known as *general* relativity. But it seems hopelessly complicated to reconcile this theory with quantum mechanics as well. Under normal circumstances, this is not needed; the way by which the gravitational force acts on the Standard Model particles, can be estimated very precisely, simply because in all situations that can be realized in experiments, this force is extremely weak. But by its very nature, gravitational forces will become strong if we endow the particles with extraordinary amounts of energy. The required energies are millions of times more than what we ever will be able to reach experimentally, and this is why gravity is usually ignored entirely in ordinary Standard Model calculations, but there is a question of principle: there is a limit to the allowed energy per particle, and we do not know how to describe their behavior if we transcend that limit. The relevant number here is called the Planck energy, 10^{19} GeV per particle; it also corresponds to the Planck length, 1.6×10^{-33} cm.

The Planck energy and length cannot be studied experimentally, since we cannot increase the power of our accelerators by a factor 10^{16}. We can, however, speculate on what might happen at such energies. One such speculation is the emergence of further unification of particles. Quarks form color triplets and weak doublets; together, these are multiplets with 6 components. Leptons are doublets and singlets. One may imagine that Yang-Mills fields exist that cause transitions between all of these quarks and leptons. An elegant scheme is obtained if quarks and leptons, and their anti-particles, are all put together into multiplets of 16 components, one 16-plet for each generation. The mathematics then tells us that the Yang-Mills bosons will form 45-plets. Most of these gauge bosons will be far too heavy to observe in machines, but we could try to compute the consequences of such theories. One consequence stands out: ordinary matter would be unstable, since protons would be able to decay into electrons and pions. This would happen very slowly. Attempts to observe such a decay event have failed until now.

Even more ambitious theories evolved from ideas that also originate from the early 1970s. At that time, theoreticians investigated what would happen in theories where particles are not at all pointlike but rather "line-like": they take the form of strings. Subjecting these strings to the laws of quantum mechanics, without first identifying particles out of which these strings could be formed, was a tour de force. It appeared to be possible, but some of the string oscillation modes behaved as if these were 'gravitons', the particles that transmit the gravitational force, or, the energy carriers of gravity. This is why string theory was then considered to replace particle physics at the Planck scale. All particles must be different string excitation modes, and the gravitational force would emerge as a natural side effect. These ideas are still being further developed. One complication is that the mathematics only works if there are more dimensions than 3 space- and one time dimension; the strings must move in 9 space dimensions. 6 of these must be curled up so as to become invisible under ordinary circumstances.

String theory originally appeared to be very powerful and very precise in its predictions. It was strongly suspected that all peculiarities of the Standard Model would soon be explained as natural consequences of string theory. This dream has not materialized, and many investigators are now giving up the hope of "explaining everything". String theory may well be correct, but possibly incomplete. Further approaches will be needed to understand the gravitational force.

6. General relativity

General relativity, in combination with quantum mechanics, must be at the basis of physical laws at the Planck scale. In some sense then, the theory combining the two should be at the basis of the most elementary building blocks of all matter. Beyond the Planck length, our conventional notions of space and time themselves appear to become meaningless. Let me first focus on general relativity without quantum mechanics.

The beautiful observations Einstein made in the first decades of the 20^{th} century is, that the gravitational force is a geometric one. The path followed by a heavy object freely falling in a gravitational field does not depend on any of its details such as mass or composition, but only on the geometrical features of space and time. It is possible to imagine *curvature* of space and time. After a considerable struggle, Einstein found the correct equations to describe curvature of space and time, as well as the motion of particles moving in a curved space-time, and the way they, in turn, affect the curvature.

Shortly after that, Carl Schwarzschild discovered that, in the case of a static, symmetric spherical object, one can solve these equations rigorously. The strange thing he found was that, if the mass of the central object would be confined within a certain radius, now called Schwarzschild radius, the gravitational field would appear to become infinite there. Schwarzschild deceased shortly after writing his paper, without fully grasping the significance of this discovery. Astrophysicists would later discover that it can indeed happen that heavy stars retreat within their Schwarzschild radius, but, if one analyzes the situation sufficiently carefully, the gravitational field does not become infinite at the Schwarzschild radius; instead, we have a "horizon" there; the escape velocity becomes equal to the speed of light. No ordinary form of matter can escape from this spot anymore. Since also light itself cannot escape, the "star" will look completely black as seen from outside. Nothing will ever be seen to come out. This configuration became known as a "black hole".

If one of the planets or planetoids of the original star would fall into the black hole, it would be torn apart and reach the speed of light there. Consequently, before reaching the Schwarzschild radius, infalling matter would evaporate and reach such tremendous temperatures that large amounts of light will be emitted. Thus, black holes often reveal their presence in a galaxy by emitting large and irregular amounts of radiation. Astronomers have identified many such objects, and numerous black holes are believed to populate our universe.

These 'astronomical' black holes will all be several times heavier than the Sun, at least, and their Schwarzschild radii will be tens of kilometers wide. For particle physics, a quite different type of black holes is of interest. If tiny particles hit each other with Planckian energies, a black hole with a Schwarzschild radius of only a few Planck lengths will be produced, more than 10^{39} times smaller than the astronomical black holes. To understand how these interact with elementary particles, one must apply the laws of quantized fields to the geometry of their space-time. Since this is primarily an exercise in geometry, it could be done, and the outcome of this analysis, first done by Stephen Hawking, is quite surprising.

Fields subject to the strange laws of quantum mechanics, show fluctuations of a type that are not possible in "classical" fields. Hawking expected space-time in the immediate neighborhood of a black hole to be empty. So he began defining this empty space. What he found instead was, that this is impossible. At its Schwarzschild radius, or 'horizon', the fluctuating fields generate particles of all types, and a steady flow of these leave the black hole. The radiation, now called Hawking radiation, has a temperature that only depends on the geometric details of the horizon and nothing else.

At first sight, this result was very welcome. It means that black holes behave much like ordinary matter; not only do they absorb particles, they also emit, as if they are steadily evaporating. From the emission rate, one could compute what its quantum states would be like, if indeed the black hole as a whole would contain quantum states, as does ordinary matter.

However, a deep and important problem showed up. Attempts to compute in detail how individual black hole quantum states would react upon objects moving inwards, led to conflicting results. Those particles that do disappear into a black hole, should also represent quantum states, but they cannot transmit information concerning their states to the outside world, because no signals can come out. In particular, the *phase* of these states cannot be retrieved, and this conflicts with the principles of quantum mechanics. We used quantum mechanics to set up our calculation, and now we obtain results that conflict with the same quantum mechanical laws. Something is wrong.

7. Basic laws?

Nothing is wrong according to string theory. While these discussions on black holes were going on, string theory evolved further. It was found that one should not only have strings, but also membranes and other, higher dimensional structures, called D-branes. Some of these D-branes occupy all of space and time, and they obey equations all by themselves. Indeed, the gravitational force, when it becomes strong, causes twists in stacks of D-branes, and the quantum states of these twisting D-branes turned out to correspond to black hole solutions. Thus, string theory generates black holes, and their quantum states can be counted. The laws of quantum mechanics appear not to be violated here, so all should be fine.

String theory, however, does not allow us to check what went wrong with the original calculation. What will an 'observer' see when he/she falls into a black hole? Is this a meaningful question? If not, why not? If black holes do return information about the phases of the infalling quantum particles back to the outside world, how would observers near the horizon describe this process?

There seems to be something wrong with the internal structure of the quantum laws here. There appears to be a fundamental *non-locality* in the basic laws at the Planck scale. Observing this, we are reminded of many long standing discussions concerning the real logical, ontological meaning of the quantum mechanical equations, or, the *interpretation* of quantum mechanics. It seems to be inevitable that this discussion should be reconsidered, but now in connection with black hole physics.

Einstein had always been unhappy with the standard interpretation of quantum mechanics. He found it strange that "God would play dice", referring to the erratic quantum fluctuations. At the Planck scale, also these fluctuations occur, but one might suspect that, there, they are not so erratic anymore. Maybe God is playing dice with a slot machine whose gears and flippers are of Planckian sizes. Integrating this to larger distance and time scales, might easily result into fundamentally random behavior. Perhaps 'quantum randomness' ceases at the Planck scale.

Fact is, that replacing quantum randomness by some controlled, pseudo-erratic but deterministic law, is extremely difficult. Most researchers take it for 'proven' that this cannot be done in a 'reasonable' theory. Delicate constructions have been proposed, but it is difficult to believe any of the proposed schemes.

We still have hopes that further clues can come from experimental observations. String theory expects that there will be 6 more space dimensions, and some consequences of such extra dimensions might become observable one day. Laboratories even larger and more ambitious than the ones that exist today, to be built with truly international efforts, are our best hopes for a further glance into this utterly weird realm of our physical world.