From maximum force to physics in 9 lines – and implications for quantum gravity

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A compact summary of present fundamental physics is given and evaluated. Its 9 lines contain both general relativity and the standard model of particle physics. Their precise agreement with experiments, in combination with their extreme simplicity and their internal consistency, suggest that there are no experimental effects beyond the two theories. The combined properties of the 9 lines also imply concrete suggestions for the search for a theory of quantum gravity. Finally, the 9 lines specify the only decisive tests that allow checking any specific proposal for such a theory.

In fundamental physics, a world-wide search for the theory of quantum gravity is under way. Despite intense attempts in experiment and theory, the search is still ongoing. So far, all experiments ever performed and all observations ever made can be described with general relativity and with the standard model of particle physics (with massive Dirac neutrinos). The world-wide search for observations beyond general relativity was unsuccessful [1–3], and so was the world-wide search for observations beyond the standard model [4].

The present article first summarizes general relativity and the standard model in a way that is as simple and as compact as possible, while keeping the precision that the two theories provide. The summary consists of 9 short lines, each of them decades old: five general principles and four lines of specific choices. Evaluating the 9-line summary highlights the open issues in the foundations of physics. The simplicity of the summary yields explicit experimental predictions. The 9 lines also define the requirements that any theory of quantum gravity must fulfill. In particular, they lead to a limited number of decisive tests. The deduced requirements and tests explain why quantum gravity has not yet been achieved, and provide guidance for future searches.

I. LEAST ACTION

In nature, all motion can be described by the principle of least action: motion minimizes action. This applies to microscopic motion. On large scales, action can also be stationary.

In everyday life, action is the time integral of the Lagrangian, i.e., of the difference between kinetic and potential energy. In general, the action is defined as the integral of a Lagrangian density based on and built with observable fields [5]. The equations of motion follow from the requirement that action is minimized – or stationary.

The history of the principle of least action is complicated and long. After the first precise description of motion by Galileo, researchers took about 150 years to complete the definition of ‘action’. In physics, action is a scalar quantity measuring the change occurring in a system. To measure it, the ability to measure length and time intervals with meter bars and clocks is required.

Experimental validation of the principle of least action occurs every day – in classical physics, in quantum theory and in general relativity. Action minimization describes every type of motion. Action minimization is valid for the motion of machines, molecules, animals, electricity and light, the motion of planets and stars, the motion of

Table 1. Nine lines describe all observations about nature.

| Nr. | Line | Details |
|-----|------|---------|
| (1) | $dW = 0$ | Action $W = \int L \, dt$ is minimized in local motion. The lines below fix the two fundamental Lagrangians $L$. |
| (2) | $v \leq c$ | Energy speed $v$ is limited by the speed of light $c$. This invariant implies special relativity and restricts the possible Lagrangians. |
| (3) | $F \leq c^4/4G$ | Force $F$ is limited by $c$ and by the gravitational constant $G$. This invariant implies general relativity and, together with lines 1 and 2, fixes its Lagrangian. |
| (4) | $W \geq \hbar$ | Action $W$ is never smaller than the quantum of action $\hbar$. This invariant implies quantum theory and restricts possible Lagrangians. |
| (5) | $S \geq k \ln 2$ | Entropy $S$ is never smaller than $O(1)$ times the Boltzmann constant $k$. This invariant implies thermodynamics. |
| (6) | U(1) | is the gauge group of the electromagnetic interaction. It yields its Lagrangian when combined with lines 1, 2 and 4. |
| (7) | SU(3) and broken SU(2) | are the gauge groups of the two nuclear interactions, yielding their Lagrangians when combined with lines 1, 2 and 4. |
| (8) | 18 particles | – gauge bosons, the Higgs boson, quarks, leptons, and the undetected graviton – with all their quantum numbers [4], make up everything and, with the interactions, fix the standard model Lagrangian. |
| (9) | Finally, 27 numbers | – dimensions, cosmological constant, coupling constants, particle mass ratios, mixing angles [4] – complete the two fundamental Lagrangians. They determine all observations and all colours. |

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particles and fields, and for the change of curvature of empty space. Falsification of least action requires finding an exception in an observation. In principle, this is possible, but the probability is low. In fact, no non-equivalent alternative to the principle of least action appears to have ever been proposed.

In short, on a small scale, all motion follows the principle of least action

\[ dW = 0 \] (1)

Microscopic motion minimizes action \( W = \int L \, dt \), i.e., minimizes the integral of the Lagrangian \( L \). The two fundamental Lagrangians of nature, the Hilbert Lagrangian of general relativity and the Lagrangian of the standard model of particle physics, are defined in the following.

II. MAXIMUM SPEED

Special relativity is based on the principle of an invariant maximum speed with a value \( c \approx 3.0 \cdot 10^8 \text{ m/s} \). In nature, energy cannot move faster than \( c \). The maximum speed itself is only achieved by massless radiation, such as light, gluons or gravitational waves. Maximum speed is the origin of the Lorentz transformations, the equivalence of energy and mass, the relativity of time, the relativity of length, and the speed addition formula, among others. The invariant limit property of \( c \) thus goes beyond a conversion factor between length and time.

Maximum speed was discovered in the years from 1860 to 1890. In 1905, Einstein deduced the Lorentz transformations from maximum speed [6]. In particular, maximum speed determines the form of any Lagrangian that complies with special relativity. In particular, because action is observer-invariant, it must be a Lorentz scalar.

In a vacuum, light from a moving lamp has the same speed as light from a lamp at rest. Experimentally, this holds in all directions [7]. Furthermore, even the lightest little ‘stones’, single electrons, cannot be accelerated faster than light, even using the largest amounts of energy. This speed limit is found to apply also to protons, neutrons, rockets, radio waves, X-rays and gravitational waves. The speed limit is so fundamental that it is used to define the meter as the path of light during a given interval of time. No type of matter and no type of radiation moves faster than \( c \). The speed limit is a local limit: it is valid for energy speeds at a single point. Sums of speeds at different locations can exceed the limit. These aspects are of importance in the next section.

Experimental validation of maximum speed is frequent. Every electric motor confirms the existence of a maximum speed. No known example of motion of energy contradicts maximum speed. Maximum speed is valid in classical physics, in quantum theory and in general relativity. Falsification means finding an example of energy moving faster than \( c \). Such an observation is possible in principle, but the probability is low. Despite high potential rewards, nobody has found a way to move energy faster than light in vacuum. Likewise, attempts to find a description of nature without maximum energy speed have not been successful.

In short, special relativity can be deduced from the principle of maximum speed:

\[ v \leq c \] (2)

There is an energy speed limit in nature. Among others, the principle requires that Lagrangians must be Lorentz-scalars.

III. MAXIMUM FORCE

In 1973, Elizabeth Rauscher discovered that general relativity implies a limit to force: she assumed that it was given by the quantal force \( F = c^4/G \) [8]. She was followed by many other researchers [9–40]. In 2002, Gary Gibbons and, independently, Schiller deduced the factor 1/4 and showed that force at a point is never larger than the maximum value \( c^4/4G \approx 3.0 \cdot 10^{43} \text{ N} \) [14, 15]. The maximum value is realized on black hole horizon. At that time, it also became clear that the field equations of general relativity can be deduced from the invariant maximum force \( c^4/4G \) [15, 16, 32, 33, 39].

The maximum force value \( c^4/4G \) is due to the maximum energy per distance ratio appearing in general relativity. Indeed, for a Schwarzschild black hole, the ratio between its energy \( Mc^2 \) and its diameter \( D = 4GM/c^2 \) is given by the maximum force value, independently of the size and mass of the black hole. Also the force on a test mass that is lowered with a rope towards a gravitational horizon – whether charged, rotating or both – never exceeds the force limit, but only when the minimum size of the test mass is taken into account. All apparent counter-examples to maximum force disappear when explored in detail [28–32, 41, 42].

A maximum force implies that space is curved. The maximum force value is realized at horizons. In fact, maximum force \( c^4/4G \) implies Einstein’s field equations of general relativity. There are at least two ways to deduce the field equations from maximum force [15, 16, 32, 33, 39]. Maximum force also implies the cosmological constant term, but does not fix its value. As a consequence, the maximum force limit can be seen as the defining principle of general relativity. The situation resembles special relativity, of which the maximum speed limit can be seen as the defining principle. The invariant limit property of \( c^4/4G \) thus goes beyond a conversion factor between curvature and energy density.

Because maximum force implies general relativity with the cosmological constant, also the usual big-bang cosmology follows from maximum force. Maximum force implies all observed aspects of gravitation.

The maximum force principle for general relativity is not the only possible principle. Other maximum quanti-
ties combining \(c\) and \(G\), such as maximum power \(c^3/4G\) [12, 19, 23, 32, 36, 37, 43–46] or maximum mass flow rate \(c^3/4G\) [32, 34], can also be taken as principles of relativistic gravity.

Attempts to find counterexamples to maximum force are not successful. In flat space and at low speeds, the maximum force value implies inverse square gravity [47], which is well established experimentally. Because the force limit is \textit{local}, an observer cannot add forces acting at different location and claim that their sum exceeds the local limit \(c^3/4G\). (Such examples are easily found.) The value \(c^3/4G\) is also the largest possible gravitational force between two black holes. Maximum force also implies the hoop conjecture [47–50]. Furthermore, maximum force eliminates most, but not all, alternative theories of gravity [32]. However, it is unclear whether modified Newtonian dynamics remains possible or is eliminated.

No counterexample to the maximum luminosity and power value \(c^3/4G \approx 9 \times 10^{31}\) W has been found. Even the most recent observations of black hole mergers fail to exceed the luminosity limit; the highest instantaneous luminosity observed so far is about 0.5% of the maximum value. Also in cosmology, no power value exceeding the limit is observed [32, 40].

Falsification of the limits is possible. It is sufficient to observe or point out a value for local force, power or luminosity that exceeds the respective limit. Every day, maximum force and general relativity are confirmed by the position determination performed by mobile phones.

In short, general relativity can be deduced from the \textit{principle of maximum force}:

\[
F \leq c^3/4G.
\]

There is a force limit in nature. Both the Hilbert action and Einstein’s field equations of general relativity can be deduced from the principle of maximum force combined with the principle of maximum speed and the principle of least action. The principle of maximum force was the last building block that allowed summarizing physics in 9 simple lines.

\section*{IV. THE QUANTUM OF ACTION}

Quantum theory is based on the invariant smallest action \(\hbar \approx 1.1 \cdot 10^{-34}\) Js. It is not possible to measure action values – i.e., changes – smaller than \(\hbar\), a constant of nature that is called the elementary quantum of action. (In fact, the smallest change is \(h = 2\pi\hbar\), but often the two quantities are used interchangeably.) The quantum of action is the origin of the indeterminacy relation. Above all, the quantum of action explains photons and atoms.

Planck discovered the quantum of action \(\hbar\) in the 1890s, when studying light. The term ‘quantum’ was introduced by Galileo, who explained that matter is made of ‘piccoliissimi quanti’, tiny quanta, that are not divisible. In 1906, Planck took over the term [51].

In nature, action is \textit{quantized}. An action value, or change, smaller than \(\hbar\) is never measured [52–55]. In addition, every action value – every measured change – is a multiple of \(\hbar\). This property also implies the quantization of angular momentum. The quantum of action is so fundamental that it is used to define the kilogram in the international system of units. The limit \(\hbar\) implies wave functions and the Schrödinger equation, the Dirac equation and all of quantum theory, including probabilities and entanglement [52]. The quantum of action \(\hbar\) modifies the principle of least action in the microscopic domain: it determines the mathematical structure of Lagrangians that correctly describe the probabilistic outcomes of experiments.

A straightforward attempt to falsify smallest action is to measure a system’s or a particle’s energy \(E\) twice, at the start and at the end of an interval \(\delta t\). Even though in the classical approximation action is given by the product \(W = E\delta t\) and can get as small as desired, in nature – and in quantum theory – the action value \(W\) remains finite when \(\delta t\) gets small: the measured energy (difference) increases when \(\delta t\) decreases. The reason is the uncertainty relation: it prevents that the measured action value approaches zero when \(\delta t\) does so.

Other attempts at finding a counter-example to the quantum of action use spin. Because action is quantized in multiples of \(\hbar\), there is no spin smaller than \(1/2\): detecting a spin \(1/2\) flip requires an action \(\hbar\). There is no way to detect a spin flip with a smaller amount of action.

A further attempt is light detection. Detecting even the dimmest light requires an action \(\hbar\). Light consists of photons. In nature, there is no way to detect one half or one hundredth of a photon. Photons are elementary quanta: they cannot be split. If \(\hbar\) were not the smallest action value, photons would not exist. Also atoms would not exist without the lower limit set by \(\hbar\). The invariant limit property of \(\hbar\) thus goes beyond a conversion factor between angular velocity and energy, or between wave number and momentum.

Action quantization is confirmed by all experiments ever performed. The discovery of \(\hbar\) led to the development of electronics, lasers, computers and the internet. Indeed, no (non-equivalent) alternative description of quantum physics has ever been proposed. Nevertheless, falsification remains possible, by measuring a smaller action value than the quantum of action \(\hbar\). It is unlikely that this will happen.

In short, combining the principle of least action with the \textit{quantum of action}

\[
W \geq \hbar
\]

implies quantum theory. In line with the above statements one can state: quantum theory can be deduced from the \textit{principle of quantized action}. The quantum of action implies the Lagrangian of quantum theory and of quantum field theory. In particular, when \(c\) is included into quantum theory, antiparticles, the Dirac equation and quantum field theory arise.
V. THE BOLTZMANN CONSTANT

Whether thermodynamics is part of fundamental physics or not has been a subject of debate. Cohen-Tannoudji, Okun, and Oriti are among those in favour [56–58]. Therefore, it is included here.

Classical thermodynamics can be seen, to a large extent, as a consequence of the principle of least action. Similarly, statistical physics can be seen as following from quantum theory. Indeed, there are uncertainty relations for thermodynamic properties. As an example, temperature $T$ and energy $U$ obey $\Delta T \Delta U \geq k/2$. This relation was first given by Bohr; it was discussed by Heisenberg and other scholars [59–61]. It suggests that entropy is similar to action, with the Boltzmann constant $k$ times $O(1)$ taking the role of $\hbar$.

Planck introduced and named the Boltzmann constant $k \approx 1.4 \times 10^{-23} \text{J/K}$ together with $\hbar$. Is $k$ a just unit conversion factor between energy and temperature or is it related to a fundamental limit? In 1929, Szilard suggested [62] that there is a smallest entropy in nature. Since then, the concept of a ‘quantum of entropy’ has been explored by many authors [56, 63–88]. Entropy is observed to be quantized in various systems: in electromagnetic radiation [74, 75], in the entropy of two-dimensional electron gases [83] and in low temperature thermal conductance [84–88]. These investigations conclude that there is a smallest entropy value, which is given by a multiple of $k$. Often, but not always, the smallest entropy is given as $k \ln 2$, as done by Szilard. In modern terms, this numerical factor expresses that the smallest possible entropy is related to a single bit.

The concept of a smallest entropy was explored in detail by Zimmermann [67–71] and by Lavenda [89]. They deduced statistical mechanics from the existence of such a smallest entropy value in nature. The invariant limit property of the smallest entropy thus goes beyond a conversion factor between temperature and energy. (As a note, combining statistical mechanics with quantum theory yields and explains decoherence.)

Entropy quantization is confirmed by all experiments ever performed. Every time a thermometer is read out and every time hot air rises, the effects of the Boltzmann constant is confirmed. Nevertheless, falsification is possible, by measuring a smaller value than the quantum of entropy. Also in this case, it is unlikely that this will happen.

It has to be stressed that the quantum of entropy does not imply a smallest value for the entropy per particle, but a smallest entropy value for a physical system. For interacting systems of particles, entropy values per particle can be much lower than the limit. In Bose-Einstein condensates, measured values for the entropy per particle reach $0.001k$ [90].

In short, there is a smallest entropy value in nature. Continuing the above collection of limits, one can state:

\[ S \geq k \ln 2 \]  

This is the principle of smallest entropy.

VI. ELECTROMAGNETISM

The theory of quantum electrodynamics is based on the U(1) gauge symmetry of electromagnetism. The gauge symmetry determines the (minimal) coupling of the Dirac equation to the electromagnetic field. The vector potential in the Dirac equation has a local phase freedom that is called gauge freedom [91]. The U(1) gauge group explains the vanishing mass of the photon, Coulomb’s law, magnetism and light. When particle properties (of line 8) are included, U(1) implies charge conservation, Maxwell’s equations [92, 93], Feynman diagrams and perturbative quantum electrodynamics. This in turn yields the change or ‘running’ of the fine structure constant and of the electron mass, as well as all other observations in the domain, without any exception.

The description provided by quantum electrodynamics and the corresponding experiments match to high precision. Deviations between calculation and experiments are possible, but have not been found yet. Clever measurement set-ups for the well-known $g$-factor of the electron yield results with 13 to 14 significant digits that all agree with calculations [94]. Even in the case of the muon $g$-factor, there is still no confirmed deviation between experiment and calculation [95, 96].

In short, combining least action, the quantum of action, maximum speed and the

\[ U(1) \text{ gauge group} \]  

with the particle properties and the fine structure constant of line 8 and 9 below, fully specifies and describes electromagnetism. The Dirac equation and the Lagrangian of QED arise in this way. For example, this explains all material properties.

VII. THE NUCLEAR INTERACTIONS

The strong and the weak nuclear interactions are based on an SU(3) and a broken SU(2) gauge symmetry. They define strong charge and weak charge, as well as all their properties and effects. For example, the gauge groups explain the burning of the Sun, radioactivity, and the history of the atomic nuclei found on Earth.

The verification of the two non-Abelian gauge theories – with all their detailed particle properties, particle reactions, and consequences for nuclear physics – took many decades [4]. The verification was completed when accelerator experiments confirmed the existence of the Higgs boson in 2012. Both gauge groups also imply the
running of the fundamental constants with energy. Attempts at falsification or even just at extension of the
gauge description – such as the search for a fifth force, grand unification, more gauge bosons, etc. – were not
successful, despite intense research all over the world [4].
Also the recent W boson mass measurement is not a con-
firmed deviation [97].
In short, the combination of least action, the quantum
of action, the speed limit and the gauge groups
\[
\text{SU}(3) \text{ and broken } \text{SU}(2) \quad (7)
\]
fully specifies and describes the nuclear interactions, in-
cluding the Lagrangians of QCD and of the weak interac-
tion, provided the particle spectrum and the fundamental
costants given in the following are included.

\section*{VIII. THE PARTICLE SPECTRUM}

The world around us is made of elementary fermions and
bosons. All matter consists of fermions: six types of
quarks and six types of leptons. All radiation is made of
gauge bosons – the photon, the W, the Z and gluons –
and of the predicted graviton. The Higgs boson, giving
mass to all particles, completes the list. The Higgs boson
also explains the breaking of SU(2) gauge symmetry.
Each elementary particle is described by mass, spin,
electric charge, weak charge, colour charge, parities,
baryon number, lepton number and the flavour quan-
tum numbers. No other particle and no other particle
property has been detected. All the particle properties
and their conservation laws have been explored in great
detail. Every two years, the Particle Data Group doc-
uments the status and experimental progress across the
world [4].
In short, everything observed is made of
\[
18 \text{ elementary particles.} \quad (8)
\]
Nature specifies these particles and their properties. One
can also speak of 18 fundamental fields. The particle
number 18 arises if all gluons are counted as one particle,
and if the coloured quarks and all the antiparticles are
not counted separately. The essence of the statement is
that the 18 fermions and bosons just mentioned suffice to
build everything observed in nature, and that they fix the
full mathematical expression for the Lagrangian of the
standard model – together with the last line. Therefore,
these elementary particles and their properties need to
appear in Table 1.

\section*{IX. THE FUNDAMENTAL CONSTANTS}

The standard model is specified with 25 characterizing
numbers. They include 15 elementary particle masses (or
more precisely, the ratios to the Planck mass), 3 coupling
constants, as well as 6 mixing angles and 2 CP phases
both in the CKM (Cabibbo-Kobayashi-Maskawa) and in
the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) mixing
matrices [4]. One parameter is redundant. Two further
characterizing numbers, the cosmological constant and
the number of spatial dimensions, determine the expan-
sion of space-time. In accordance with all present ex-
periments, nature is described by 27 fundamental constants.
Because the constants run with energy, the precise state-
ment is that nature is described by 27 fundamental con-
stants at some defined energy value. Together, these 27
specific numerical values determine the remaining details
of the Hilbert Lagrangian and of the standard model La-
grangian.
The last fundamental constants in the standard model
Lagrangian have been introduced in the 1970s. All the
values are being measured with a precision that usually
increases when new experiments are performed [4]. At
present, the fundamental properties of the neutrinos are
the least precisely known. The cosmological constant in
the Lagrangian of general relativity has been introduced
more than a century ago. After a complicated history,
its value was first measured in the 1990s.
Neither general relativity nor the standard model ex-
plain the values of the fundamental constants. Explain-
ing these values – which include the mass of the electron
and the fine structure constant \(1/137.036(1)\) – remains
an open issue. These two constants almost completely
determine the colours in nature. As long as the numbers
are unexplained, colours are not fully understood.
Various attempts to reduce the number of fundamen-
tal constants have been proposed. Most attempts predict
new effects that have not been observed. Other propos-
als, such as certain kinds of supersymmetry, require ad-
ditional fundamental constants. However, no additional
fundamental constant has yet been discovered [4].
In short, together with the previous lines, nature spec-
fies
\[
27 \text{ fundamental constants} \quad (9)
\]
that completely determine the Hilbert Lagrangian of gen-
eral relativity as well as the Lagrangian of the standard
model of particle physics.

\section*{X. A SUMMARY OF PRESENT PHYSICS}

Lines 1, 2, 3 and 9 fully determine the Hilbert La-
grangian, including the cosmological constant. The
derivation is found in references [32] and [39]. Line 5
determines thermodynamics [67–71, 89]. All lines except
3 and 5 fully determine the Lagrangian of the standard
model of particle physics. The full expression of the La-
grangian is found, part by part, in reference [4]. The
corresponding lines in Table 1 have exactly the same
physical and mathematical content, while avoiding the
algebraic details.
While the number of lines in Table 1 is subjective, the
content is not. The number could easily be expanded or
reduced by one or two lines, while keeping the same content. Whatever form is chosen, the content of the lines in Table 1 agrees with all experiments. Only standard textbook physics is included. No part of standard textbook physics is missing.

Table 1 resulted from the work of many thousands of scientists and engineers during 400 years. Galileo started around the year 1600, with the first-ever measurements of the dynamics of moving bodies. Line 1, the principle of least action, was fully formulated around 1750. Line 5, on thermodynamics, arose from 1824 to 1929, and line 6, on electrodynamics, arose around 1860. Line 2, on maximum speed came around 1890, and line 4, about the quantum of action, around 1900. Line 3, on maximum force, grew in the years from 1915 to 2002. As a result, the Hilbert Lagrangian of general relativity agrees with experiments since more than 100 years. The remaining lines 7 to 9, on the standard model, arose in the years from 1936 to 1973. The standard model Lagrangian of particle physics thus agrees with experiments since about 50 years.

Given that no observation contradicts these equations, one can say that the 9 lines contain all present knowledge about nature, including all textbook physics and all observations ever made. The 9 lines also contain chemistry, material science, biology, medicine, geology, astronomy and engineering. This is the conclusion of a world-wide and decade-long effort to evaluate the 9 lines. The simplicity of the 9 lines and their vast domain of validity form an intriguing contrast.

The 9 lines consist of five general principles and four lines of specific choices from an infinity of possibilities. The complexity of the last four lines leads to many questions.

In short, the 9 lines of Table 1, five principles and four set of choices, contain the evolution equations of the standard model, of general relativity and of thermodynamics. They describe all of nature. The qualitative difference between the principles and choices contained in the 9 lines leads to questions.

XI. ARE THERE MORE THAN 9 LINES?

Candidates for disagreement between the 9-line summary and experiment arise regularly. Examples are W mass measurements, the muon \( g - 2 \) measurements, dark energy, dark matter, the rotation curves of galaxies, or table-top quantum gravity. It could be that an experiment of this kind one day will require changes in the 9 lines. Therefore, these and other candidates for disagreement are being explored around the world in great detail. Even though no confirmed observation is unexplained by the 9 lines, the experimental quest for such an effect will never be over.

Are unexplained observations possible at all? In other terms, are additional lines necessary to describe nature? The simplicity and consistency of the 9 lines suggest a negative answer. So far, proposals for physics beyond the standard model either require more lines, like supersymmetry, or, if they don’t, like grand unified theories, they disagree with experiment [98]. Nevertheless, a future unexplained observation cannot be excluded.

In short, any observation or experiment unexplained by the 9 lines will create a sensation.

XII. ARE THERE FEWER THAN 9 LINES?

Each of the 9 lines in Table 1 generates a question about its origin. In particular, one can ask for the origin of the five principles listed in the lines 1 to 5. So far, no accepted explanation for the origin of the principle of least action nor for the other limit principles has been proposed. It is unclear how nature enforces its five principles. In modern terms, it is unclear how the principles emerge from an underlying description.

The lack of explanation is especially evident in lines 6 to 9. These four lines contain all the specific choices that fix the details of the standard model and of general relativity. At present, the origins of the force and particle spectra are unknown, as is the origin of each fundamental constant. One can say that so far, these four lines are the only known observations beyond the standard model and beyond general relativity. However, despite multiple and intense efforts, no explanation for the four lines of specific choices has been successful and accepted. The mechanism of their emergence is unclear.

The lack of explanations and the successful description of nature with Table 1 leads to a related question: can the 9 lines be deduced from a smaller set? All these queries are part of the other, the theoretical quest being pursued in fundamental physics.

The five principles of lines 1 to 5 are not good candidates to shorten Table 1, because they are independent of each other. Sometimes, it is even suggested that the five principles are incompatible. The incompatibility between general relativity and quantum theory is often called a contradiction. Table 1 suggests that this is not the case, and that, instead, the principles complement each other. Whatever the outcome of this discussion, it appears impossible to reduce the number of principles in lines 1 to 5. Only a radical explanation based on emergence might have a chance to reduce their number.

In contrast, reducing the number of specific choices given in lines 6 to 9 should be possible. The specific choices are so particular that they cannot be fundamental; those four lines must hide a deeper explanation. The four lines must be due to an emergent explanation. In the past five decades, various proposals to reduce the number of lines 6 to 9 – or simply their details – have been made. However, no proposal agrees with observations to full precision.

In short, so far, a description of nature with less than 9 lines must exist. So far, it has not been found. Nevertheless, Table 1 implies that there is hope.
XIII. WHERE TO SEARCH FOR QUANTUM GRAVITY

The 9 lines provide several hints pointing towards an explanation based on emergence. Combining the experimental limits on speed $v$, force $F$ and action $W$ using the general relation for energy $E = Fvt = W/t$ leads to a limit on measurements of time $t$ given by

$$ t \geq \sqrt{\frac{4\hbar G}{c^5}}. \quad (10) $$

The five principles thus eliminate instants of time and introduce a minimum time interval, given by $\sqrt{4\hbar G/c^5} \approx 1.1 \times 10^{-43}$ s, twice the Planck time. In the same way, the principles also eliminate points in space and introduce a minimum distance. As a consequence, spatial continuity is not intrinsic to nature, but due to averaging. In particular, the existence of a smallest length and time interval implies that quantum theory and general relativity never actually contradict each other.

As a further consequence of a smallest measurable length, other spatial dimensions cannot arise. There is no way to ever detect or measure additional spatial dimensions.

In addition, the five principles use time and space but forbid the existence of points and instants. Therefore, the five principles prevent an axiomatic description of nature. Despite Hilbert’s dream of an axiomatic description of physics, the five principles only allow a consistent and (logically) circular description of nature.

All experiments that confirmed lines 6 to 9 make a further, less obvious statement. The specific choices contained in these four lines imply that additional interactions, additional particles, or additional constants would greatly increase the complexity of the table – in contrast to observations.

In a final description of nature and quantum, space and particles must emerge from some common description. The common description must be based on common degrees of freedom that describe extended space, localized particles, probabilistic quantum motion, and a minimum distance. There is only one possible conclusion: space and particles must be made of fluctuating constituents. To realize the minimum length, the constituents must be of minimum size, i.e., of Planck size, in at least one dimension. To realize the macroscopic extension of space, the constituents must have at least one macroscopic dimension.

One notes that many approaches in the literature are eliminated by these conclusions. In fact, these conclusions explain why the search for a complete description of motion was not successful so far: almost no approach towards quantum gravity uses extended fluctuating constituents with both macroscopic and Planck dimensions.

In short, the 9 lines of Table 1 imply the existence of a smallest distance. The 9 lines further imply that the description of space and of the known particles must emerge from constituents that are spatially extended. This conclusion allows a number of predictions on how to achieve an even shorter summary of physics.

XIV. PREDICTIONS ABOUT THE THEORY OF QUANTUM GRAVITY

The 9 lines summarizing physics lead to two sets of testable predictions. The first set concerns future experiments.

Pr. 1. Lines 2 to 5 imply that no trans-Planckian quantities or effects arise in nature. This is valid for length, time and for every other physical observable. The precise limits are given by the (corrected) Planck limits, such as the minimum length $\sqrt{4\hbar G/c^5}$, the minimum time $\sqrt{\frac{4\hbar G}{c^5}}$ or the maximum force $c^4/4G$. Here, the factor 4 from maximum force corrects the commonly used Planck units. (For some cases, such as Planck energy or Planck momentum, the derivation of the limit is only valid for a single elementary particle.) For example, space-time cannot be described by foam, as foam assumes the existence of points and manifolds up to infinitely small scales. The experimental agreement and the simplicity of the limits in lines 2 to 5 further imply that these limits also apply in quantum gravity. All these aspects are in agreement with all experiments.

Pr. 2. On the other end of the scale, using the cosmological constant $\Lambda$ from line 9, a cosmological limit can also be deduced for every observable: there is a maximum length, a maximum time, etc. The prediction of the lack of infinitely large and of infinitely small observables was already made by Hilbert [99]. The prediction is in agreement with all experiments.

Pr. 3. A continuous space-time in spite of the existence of a minimum distance implies that locality, continuity and causality are valid at all observable scales, i.e., at all scales larger than the Planck scale. This prediction agrees with all data so far.

Pr. 4. The 9 lines predict that there is no physics beyond special relativity, beyond general relativity, beyond thermodynamics, beyond quantum theory and beyond the standard model. The nine lines predict the lack of any additional symmetries, structures or effects whatsoever, at any length or energy scale: the lines predict the so-called high-energy desert. In the past centuries, mistaken predictions about the lack of new physics have been made several times. At present however, there is a difference: the prediction agrees with all high-precision observations since over five decades.

The listed predictions can be all seen as specific aspects of the predicted lack of new physics. In addition to the experimental predictions, the 9 lines imply a set of theoretical predictions about quantum gravity.
Pr. 5. It was shown above that the limits \( c, \frac{c^4}{4G}, \hbar \) and \( O(1)k \) define special relativity, general relativity, quantum theory and thermodynamics. In the same way, the limits arising when combining the theories – i.e., when combining the four limits – *define* quantum gravity. More precisely, the 9 lines imply that quantum gravity is already known in all its experimental and theoretical effects: quantum gravity implies the five principles of line 1 to 5 and it fixes the choices of lines 6 to 9. In other words, quantum gravity is predicted to be *close*, both experimentally and conceptually.

Pr. 6. Minimum length and time intervals imply that space and time are *not* made of points. Likewise, point particles do *not* exist. Space, time and particles must be made of a different type of microscopic constituents. These microscopic constituents must differ from points in two ways: first, they must have, in one dimension, a size given by the smallest length, and thus they must be *discrete*, i.e., countable. Secondly, they must reproduce the extension of space, and thus be *spatially extended* in another dimension. The first property is generally expected; for example, the property implies and confirms the finiteness of black hole entropy, the Bekenstein entropy bound [100] and the maximum entropy emission rate [101]. The second property, the extension of the microscopic constituents, is realized in various approaches to quantum gravity.

Pr. 7. Because the limits \( c, \frac{c^4}{4G}, \hbar, O(1)k \), and all their combinations hold also in quantum gravity, and because the microscopic constituents are discrete and spatially extended, any continuity observed in nature arises through *averaging*. The microscopic constituents require a probabilistic description of fluctuations. For example, space cannot be a lattice of points or some other structure that is fixed in time. In other terms, *continuity emerges from averaging microscopic fluctuating constituents*.

Pr. 8. Because continuity arises in all settings – and despite the existence of a smallest length and time – space and time can be used to describe nature. In fact, because the limits \( c, \frac{c^4}{4G}, \hbar, \) and \( k \) remain valid and because all the limits contain meter and second in their units, space and time must be used to describe nature. For example, this implies that, in practice, there is no problem about the origin of time. A description of nature without space and time is predicted to be impossible. Both space and time emerge from the microscopic constituents via averaging. This argument also implies that quantum gravity must continue to use – as is done by general relativity and by the standard model – one-dimensional time and three-dimensional space. The lack of trans-Planckian effects prevents the observability, the influence and the existence of other dimensions of space-time.

Pr. 9. Because the 9 lines of Table 1 contain only simple algebra, they suggest that any future, shorter set of statements describing all of physics will again contain only *simple mathematics*. In other terms, the microscopic constituents are predicted to show *simple behaviour*. In particular, the five principles in lines 1 to 5 are predicted to *emerge* from the collective aspects of this fundamentally simple behaviour. This requirement is realized by various microscopic models proposed in the research literature, in particular by models for quantum gravity that fulfil the Planck limits using fluctuating constituents.

Pr. 10. Also the specific choices in lines 6 to 9 are predicted to *emerge* from the microscopic constituents. This is a demanding requirement; so far, it is *not fully realized* by any proposed kind of microscopic constituents. In particular, the microscopic constituents must explain the gauge groups, the spectrum of elementary particles, their mass values, their mixing angles, the values of the coupling constants, the cosmological constant and the number of spatial dimensions.

In short, general relativity and the standard model – including space, gravity, particles and horizons – are predicted to emerge from fluctuating extended constituents in three effective spatial dimensions. In total, none of the experimental and theoretical predictions has yet been falsified, even though many research approaches disagree.

XV. GUIDANCE FOR FUTURE SEARCHES

The predictions just given do not seem to be found in publications. Above all, the predictions underline why past approaches for quantum gravity were not successful. The main reason is found in the last prediction. As long as Table 1 remains valid checking lines 6 to 9 are the only possible tests for the correctness of any proposed microscopic constituents. Among these tests, explaining the last line is decisive.

Line 9 specifies the masses of elementary particles (or, equivalently, the mass ratios to the Planck mass), the coupling constants and the mixing angles. These pure numbers are fundamental constants that describe the world around us. These fundamental constants are not yet explained by any research approach that also agrees with the first 5 lines. The avoidance of the topic is the main reason that unsuccessful research approaches are not shelved. First candidates that follow this approach and that promise to agree with all predictions are appearing [102–105].

Line 9 also specifies the number of dimensions and the cosmological constant. Also these two numbers describe the world around us and must be explained. It is highly probable that the explanation of these numbers, and of the number of dimensions in particular, will be the same as for the other numbers in line 9.

In short, in the search for quantum gravity, the most productive way forward is to propose new microscopic models that realize the five principles, and then to check their consequences for the choices of lines 6 to 9.
XVI. CONCLUSION AND OUTLOOK

Present physics – experiment and theory – can be condensed in 9 lines that describe all observations and determine the two Lagrangians of physics: that of general relativity and that of the standard model. The lines consist of the five principles of least action, of maximum speed, of maximum force, of action quantization and of smallest entropy, together with four lines of specific choices for the gauge interactions, the elementary particles, and the fundamental constants.

The main experimental prediction of the 9 lines is the lack of any effect beyond general relativity and beyond the standard model of particle physics. The main theoretical prediction is that discrete and spatially extended fluctuating constituents in 3 + 1 dimensions will explain all 9 lines. Because no new effects are expected, the decisive tests of any proposed theory of quantum gravity are calculations of the measured values for the elementary particle masses, for the mixing angles and for the coupling constants.

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