Present physics in 9 lines – and predictions for its future

Christoph Schiller [*]
Motion Mountain Research, 81827 Munich, Germany

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A compact and precise summary of fundamental physics is proposed and evaluated. Its 9 lines contain general relativity and the standard model of particle physics, and thus agree with all experiments so far. The summary highlights the open issues in the foundations of physics. The 9 lines also provide experimental predictions and suggestions for future research.

In fundamental physics, a world-wide search for the final theory is under way. Despite intense attempts in experiment and theory, the search is still ongoing. Indeed, 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 aim of the present article is to summarize general relativity and the standard model in a way that is as simple and as compact as possible, while keeping the precision of the description that the two theories provide. The summary consists of 9 short lines: five general principles and four lines of specific choices. These 9 lines are useful for teaching and for highlighting the open issues in the foundations of physics. Above all, the simplicity of the summary yields explicit experimental predictions and provides specific suggestions about the search for a final theory.

I. LEAST ACTION

In nature, all motion can be described by the principle of least action: *motion minimizes action.* This applies to small-scale motion in particular. (On large scales, action can be stationary.) In nature, we observe motion of matter, motion of radiation, and motion of space-time. In all cases of motion, action is defined as the integral of a Lagrangian density.

The principle of least action is so fundamental for physics that the 10-volume Landau-Lifshitz textbook on theoretical physics starts with action on its first page [5]. In everyday life, action is the time integral of the Lagrangian, i.e., of the difference between kinetic energy and potential energy. In other settings, the action is defined in a more general manner. In all cases, action is a measure for the *change* occurring in a physical system. All equations of motion follow from the requirement that action, defined accordingly, is minimized.

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 sort out the definition of 'change'. The definition was finalized around 1750.

Table 1. Nine lines describe all observations about nature.

Nr.	Line	Details
(1)	$\mathrm{d}W = 0$	Action $W = \int L\,\mathrm{d}t$ 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 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 implies general relativity and fixes its Lagrangian.
(4)	$W \geq \hbar$	Action W is never smaller than the quantum of action $\hbar$. This implies quantum theory and restricts possible Lagrangians.
(5)	$S \geq k \ln 2$	Entropy S is never smaller than $\mathcal{O}(1)$ times the Boltzmann constant k. This implies thermodynamics.
(6)	U(1)	is the gauge group of the electromagnetic interaction. It yields its Lagrangian.
(7)	SU(3) and broken SU(2)	are the gauge groups of the two nuclear interactions, yielding their Lagrangians.
(8)	18 particles	– gauge bosons, the Higgs boson, quarks, leptons, and the undetected graviton – with all their quantum numbers, make up everything and, with the interactions, fix the standard model Lagrangian.
(9)	Finally, 27 numbers	– dimensions, cosmological constant, coupling constants, particle mass ratios, mixings – complete the two fundamental Lagrangians. They determine all observations and all colours.

Experimental validation of least action occurs every day. Action minimization is valid in classical physics, in quantum theory and in general relativity. Action minimization is valid for motion of stones, air, lightning, electricity and light, for the growth of trees and of mountains, for the motion of particles, fields, planets and stars, and for the change of curvature of empty space. Falsification just requires finding an exception to least action in a single experiment. This is possible in principle, but the probability is low. In fact, no (non-equivalent) alternative to the principle of least action appears to have ever been proposed.

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[*] cs@motionmountain.net

In short, motion minimizes action W. All motion follows the *principle of least action*

$$\mathrm{d}W = 0 \ . \tag{1}$$

Equivalently, all motion minimizes change. 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 c. Energy cannot move faster than c. The maximum speed is only realized by massless radiation. The maximum speed is the origin of the Lorentz transformations, the equivalence of energy and mass, the relativity of time, the relativity of length and of the speed addition formula, among others.

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 c determines the form of any Lagrangian that complies with special relativity. For example, because action is observer-invariant, it must be a Lorentz scalar.

Throwing a stone while running yields a greater speed v than throwing it standing still. However, in a vacuum, light from a moving lamp is not faster than light from a lamp at rest. 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 limit also applies to protons, neutrinos, rockets, radio waves, X-rays or 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. In contrast, geometric features, such as images or shadows, can move faster than c. One also notes that the speed limit is a local limit: it is valid for speeds at a single point. Sums of speeds at different locations can exceed the limit.

Experimental validation of maximum speed is frequent. No known example of motion contradicts maximum speed. Maximum speed is valid in classical physics, in quantum theory and in general relativity. Falsification means finding just one 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. Attempts to find a description of nature without maximum speed have not been successful.

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

$$v \leq c \ . \tag{2}$$

There is an energy speed limit in nature.

III. MAXIMUM FORCE

In 1973, Elizabeth Rauscher discovered that general relativity *implies* a limit to force: she assumed that is was given by the quantal force $F = c^4/G$ [8]. She was followed by many other researchers [9–38]. In 2002, Gary Gibbons and others specified the factor 1/4 and showed that local force is never larger that the maximum value $c^4/4G \approx 3.0 \cdot 10^{43}$ N [14]. In the past decades, it became clear that the field equations of general relativity can be *deduced* from the invariant maximum force $c^4/4G$ that is realized on gravitational horizons [15, 16, 33, 34]. As a result, even cosmology follows from maximum force.

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 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, *when* the minimum size of the test mass is taken into account. All apparent counterexamples to maximum force disappear when explored in detail [28–31, 33, 39, 40].

The maximum force value is realized at horizons. A maximum force also implies that space is curved. In fact, maximum force $c^4/4G$ *implies* Einstein's field equations of general relativity. Maximum force also implies the cosmological constant term, but does not fix its value. There are at least two ways to deduce the field equations from maximum force [15, 16, 33, 34]. 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 maximum force principle for general relativity is not the only possible principle. Other maximum quantities combining c and G, such as maximum power $c^5/4G$ [12, 19, 23, 33, 36, 37, 41–44] or maximum mass flow rate $c^3/4G$ [32, 33], 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, maximum force value implies inverse square gravity, which is well established experimentally. Because the force limit is *local*, an observer cannot add forces acting on distant masses and claim that their sum exceeds the local limit $c^4/4G$. (Such examples are easily found.) The value $c^4/4G$ is also the largest possible gravitational force between two black holes. Maximum force also implies the hoop conjecture [45–47]. Maximum force also eliminates most, but not all, alternative theories of gravity [33]. For example, it is unclear whether modified Newtonian dynamics remains possible or is eliminated.

Also no counterexample to the maximum luminosity $c^5/4G$ 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. Even in cosmology no higher power value is observed [33].

By observing or pointing out a local force, power or luminosity that exceeds the respective limit, falsification is possible at any time. So far, nobody managed to do so.

In short, general relativity can be deduced from the *principle of maximum force:*

$$F \leq c^4/4G \ . \tag{3}$$

On other terms, 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. (As a note, only the principle of maximum force completes the beautiful simplicity of the 9 lines.)

IV. THE QUANTUM OF ACTION

Quantum theory is based on the invariant smallest action $\hbar$. 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. (Actually, the smallest change is $h = 2\pi\hbar$, but nowadays the two quantities are often used interchangeably.) The quantum of action is the origin of the indeterminacy relation. Above all, the quantum of action explains photons and atoms. Whenever a process approaches the action limit, probabilities arise. The limit $\hbar$ implies wave functions and the Schrödinger equation, and all of quantum mechanics, including probabilities and entanglement.

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 'piccolissimi quanti', tiny quanta that are not divisible. In 1906, Planck took over the term [48]. Despite being a modest man, he was conscious that he made, by chance, an important discovery: an unknown fundamental property of nature.

In nature, action is *quantized.* An action value, or change, smaller than $\hbar$ is never measured [49–51]. In addition, every action value, every measured change, is a multiple of $\hbar$. The quantum of action is so fundamental that it is used to define the kilogram in the international system of units. The limit given by $\hbar$ also implies the quantization of angular momentum.

The easiest falsification attempt is to measure a particle's energy at two different points in time. Even though, classically, action W is given by energy $E\,\delta t$, in nature and in quantum theory the action value W remains finite when δt gets small. This is because of the uncertainty relation: the energy (difference) increases when δt decreases. (Measuring energy requires time, and that time must be shorter than δt.) For small δt, the quantum of action $\hbar$ in the uncertainty relation prevents that the measured action goes to zero when δt goes to zero.

Other attempts at finding a counter-example 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 just no way to detect one half or one hundredth of a photon. Photons are elementary: they cannot be split. If $\hbar$ were not the smallest action value, photons would not exist. (Similarly, atoms would not exist either.)

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

In short, combining the principle of least action with the quantum of action

$$W \geq \hbar \tag{4}$$

implies quantum theory. In line with the above statements one can say: quantum theory can be deduced from the *principle of quantized action.* 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 [52–54].

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 $\Delta 1/T \; \Delta U \geq k/2$. This relation was first given by Bohr; it was discussed by Heisenberg and many others [55–57]. It suggests that entropy is similar to action, with the Boltzmann constant k times $\mathcal{O}(1)$ taking the role of $\hbar$.

Planck introduced and named the Boltzmann constant k together with $\hbar$. Is k a unit conversion factor between energy and temperature or does it have a deeper meaning? The issue can be clarified by asking whether k is related to a fundamental limit. In 1929, Szilard answered positively [58] and suggested that there is a smallest entropy in nature. Since then, the concept of a 'quantum of entropy' has been explored by many authors [52, 59–84]. Entropy is observed to be quantized in various systems: in electromagnetic radiation [70, 71], in the entropy of two-dimensional electron gases [79] and in low temperature thermal conductance [80–84]. 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 [63–67] and by Lavenda [85]. They deduced statistical mechanics from the existence of such a smallest entropy value in nature.

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. Measured values for the entropy per particle reach $0.001k$, as observed in Bose-Einstein condensates [86].

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

$$S \geq k \ln 2 \quad . \tag{5}$$

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 [87]. The U(1) gauge group explains the vanishing mass of the photon, Coulomb's law, magnetism and light. When particle properties (see line 8) are included, U(1) implies charge conservation, Maxwell's equations [88, 89], Feynman diagrams and perturbative quantum electrodynamics. This in turn yields the 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 [90]. Even in the case of the muon g-factor, there is still no confirmed deviation between experiment and calculation [91, 92].

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

$$\text{U(1) gauge group} \tag{6}$$

with the particle properties and the fine structure constant of line 8 and 9 below, fully specifies and describes electromagnetism. For example, all material properties and all colours are explained in this way.

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 their consequences for nuclear physics – took many decades [4]. The result was complete 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 confirmed deviation [93].

In short, the combination of least action, the quantum of action and the gauge groups

$$\text{SU(3) and broken SU(2)} \tag{7}$$

fully specifies and describes the nuclear interactions, provided the particle spectrum and the fundamental constants given in the following are included.

VIII. THE PARTICLE SPECTRUM

The world around us is made of elementary fermions and bosons. All matter consists of fermions: six quarks and six 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 mentioned 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 quantum 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 documents the status and experimental progress across the world [4].

In short, everything observed is made of

$$\text{18 elementary particles.} \tag{8}$$

Nature specifies these particles and their properties. 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 fermions and bosons just mentioned suffice to build everything observed in nature. Therefore, these elementary particles and their properties need to appear in Table 1.

IX. THE FUNDAMENTAL CONSTANTS

The standard model is specified with 25 characterizing numbers. They include 15 particle masses (or more precisely, the ratios to the Planck mass), 3 coupling constants, as well as 6 mixing angles and 2 CP phases in the CKM (Cabibbo-Kobayashi-Maskawa) and in the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) mixing matrices [4]. One parameter is redundant. Another couple of characterizing numbers, the cosmological constant and the number of spatial dimensions, determine the expansion of space-time. At present, nature is described by 27 fundamental constants. Together, these 27 specific numerical values fix the remaining details of the Hilbert Lagrangian and of the standard model Lagrangian.

The last fundamental constants 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.

Neither general relativity nor the standard model explain the values of the fundamental constants. Explaining these values – which include the mass of the electron and the fine structure constant 1/137.036(1) – remains an open issue.

Numerous attempts to reduce the number of fundamental constants have been proposed. So far, most attempts predict new effects that have not been observed. Other proposals, such as certain kinds of supersymmetry, may require additional fundamental constants; however, no additional fundamental constant has yet been observed.

In short, together with the previous lines, nature specifies

$$\text{27 fundamental constants} \tag{9}$$

that completely determine the Hilbert Lagrangian of general relativity as well as the Lagrangian of the standard model of particle physics.

X. A SUMMARY OF PRESENT PHYSICS

Lines 1, 2, 3 and 9 fully determine the Hilbert Lagrangian, including the cosmological constant. The Lagrangian is found in every textbook on general relativity. Line 5 determines thermodynamics. All lines except 3 and 5 fully determine the Lagrangian of the standard model of particle physics. The full expression of the Lagrangian is found, part by part, in reference [4]. When written with all terms and ghosts, the standard model Lagrangian takes about a full page. The form popularized by Thomas Gutierrez (in which neutrinos still have no mass) is often shown [94]. The corresponding lines in Table 1 have exactly the same physical and mathematical content, while avoiding the algebraic details. Single-line expressions found on mugs or T-shirts usually lack most details from lines 6 to 9. Sometimes even the combined Lagrangian of gravity and particle physics is reduced to a singe line. For example, this is done by David Tong in his popular lectures [95]. While including a large part of Table 1, such a single line expression misses most of the details included in lines 8 and 9.

The total number of lines in Table 1 is obviously subjective. The number could easily be expanded or reduced, while keeping the same content. But the content of the 9 lines is objective. 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. Indeed, the standard model Lagrangian of particle physics agrees with experiments since about 50 years.

In short, the 9 lines contain all the Lagrangians and thus all the evolution equations of the standard model and general relativity. 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 present status of a world-wide effort to evaluate the 9 lines. The simplicity of the 9 lines and their vast domain of validity form a fascinating contrast.

XI. ARE THERE MORE THAN 9 LINES?

Candidates for disagreement between theory 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 such an experiment will require changes in the 9 lines in the future. Therefore, these and other candidates are being explored around the world in great detail. So far, there is no confirmed observation that is not explained by the 9 lines. But the *experimental quest* for disagreement will never be over.

Are unexplained observations possible at all? In other terms, are additional lines necessary to describe nature? These questions lead to intense debates. A definite answer cannot be given.

In short, a single 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, there is no explanation for the origin of the principle of least action, and there is also no explanation for the other limit principles. It is unknown how nature 'enforces' its five principles.

The lack of explanations also concerns the remaining lines. At present, the origins of the force and particle spectra are unknown, as is the origin of each fundamental constant. The lines 6 to 9 contain all the *specific choices* that fix the details of the standard model and of general relativity. One can say that so far, these 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.

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

The five principles of lines 1 to 5 are not good candidates for a shorter version of Table 1, because they are independent of each other. Even worse, they have a property that prevents shortening this part of the table. Combining the limits on speed v, force F and action W using the general relation $Fvt = W/t$ leads to a limit on measurements of time t given by

$$t \geq \sqrt{4G\hbar/c^5} \ , \tag{10}$$

i.e., twice the Planck time. The limit principles thus *eliminate instants of time.* In the same way, the limits also *eliminate points in space.* As a result, the five limits *prevent* an axiomatic description of physics. This property is often phrased by stating that the five principles are incompatible. Often, an incompatibility or even a contradiction is assumed between general relativity's principle of maximum force and quantum theory's principle of action quantization. Table 1 suggests that this might not be the case, and that, instead, the 9 lines complement each other. Whatever the outcome of this discussion, it appears hard to reduce the number of principles in lines 1 to 5.

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. But despite 50 years of attempts, *no* proposal to reduce the number of lines with choices – or even just their details – agrees with observations to full precision. Nevertheless, Table 1 implies that there is hope.

XIII. PREDICTIONS ABOUT THE FINAL DESCRIPTION OF MOTION

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

Pr. 1. Lines 2 to 5 suggest that *no infinitely large or small quantities* arise in nature. This is valid for length, time and for every other physical observable. On one end of the scale, the limits are given by the (corrected) Planck values, such as the minimum length $\sqrt{4G\hbar/c^3}$ or the minimum time $\sqrt{4G\hbar/c^5}$. Here, the factor 4 from maximum force corrects the commonly used Planck units. For example, a limit on length measurements also implies that no experiment will observe singularities, discrete space-time, additional space-time structures, or additional dimensions. Of the other end of the scale, using the cosmological constant Λ from line 9, a second limit can also be deduced for every observable: there is a maximum length, a maximum time, etc. The prediction of the lack of infinite observables in nature not new. The prediction agrees with all experiments so far.

Pr. 2. The simplicity of the limits in lines 2 to 5 suggests that these limits *also apply* in the complete description of nature. This means that there is no physics beyond special relativity, beyond general relativity, beyond quantum theory, and beyond thermodynamics. In other words, these lines predict the *lack of any trans-Planckian physics, measurement, or effect.* In particular, the lines predict the *lack of finite observable values* that exceed the Planck limits. (For some cases, such as Planck energy or Planck momentum, the derivation of the limit is only valid for a single elementary particle.) The lack of trans-Planckian effects again imply the impossibility of many conjectured microscopic space-time structures. The prediction is quite unpopular, but is in agreement with all experiments so far.

Pr. 3. A continuous space-time despite of the existence of a minimum distance implies that *locality, continuity and causality are valid* in nature – at all scales larger than the Planck scale. No exceptions are predicted to be detectable, because distances shorter than the minimum length cannot be observed. This prediction agrees with all data so far.

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

These experimental predictions are valid as long as the 9 lines continue to describe all observations. In addition, the 9 lines imply a set of theoretical predictions about the complete description of nature.

Pr. 5. It was shown above that the limit c defines special relativity, the limit $c^4/4G$ defines general relativity, the limit $\hbar$ defines quantum theory, and k defines thermodynamics. In the same way, the limits arising when combining the theories – i.e., when combining c, G, Λ, $\mathcal{O}(1)\,k$ and $\hbar$ – *define* the final description of motion. The 9 lines thus suggest that the final description of motion is already known *in all its experimental and theoretical effects:* it simply implies Planck limits (corrected by using $4G$ instead of G) for all observables and it fixes the choices of lines 6 to 9. In other words, the final description of motion 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. For example, space can be a manifold only approximately. Therefore, for example, space-time cannot be described by foam, as foam assumes the existence of points and manifolds up to infinitely small scales. In fact, as a consequence of minimal length and time intervals, the microscopic constituents that make up space, time and particles must differ from points in two ways: they must be *discrete*, and they must be *spatially extended.* This is generally expected; for example, the conclusion implies and confirms the *finiteness* of black hole entropy.

Pr. 7. Because the limits c, $c^4/4G$, $\hbar$, $\mathcal{O}(1)\,k$, and all their combinations hold also in the complete theory, the microscopic constituents are *unobservable.* Because the microscopic constituents are discrete, spatially extended and unobservable, the continuity observed in nature arises through averaging. The microscopic constituents thus 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 results 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, $c^4/4G$, $\hbar$, and k remain valid and all 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. In addition, this implies that the final theory uses one-dimensional time and three-dimensional space.

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 *several* microscopic models proposed in the research literature.

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, no kind of microscopic constituents has been shown to realize the requirement. For example, the microscopic constituents must explain the gauge groups, the particle spectrum, the particle mass values and the values of the coupling constants. In fact, as long as Table 1 remains valid, lines 6 to 9 are the *only* way to check the correctness of any proposed microscopic constituents. Proposing new microscopic models and checking their consequences for lines 6 to 9 seems to be the only path forward on the way towards a final theory.

XIV. CONCLUSION AND OUTLOOK

Present physics – experiment and theory – can be condensed in 9 lines that describe all observations and determine the Lagrangians of physics. 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 new physics beyond general relativity and beyond the standard model of particle physics. The main theoretical prediction is that discrete and spatially extended microscopic constituents in $3 + 1$ dimensions will explain all 9 lines, and in particular the values of the particle masses and of the coupling constants. Experiments, proposals for constituents, and calculations will allow testing these predictions.

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