Answers to the 21 Einstein questions

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Here are brief answers to the Einstein questions raised in the Preface. More details and pertinent context are given in the text with the relevant chapter and section numbers as shown.

1. In Einstein's doctoral thesis (Chapter 1), he derived two ways of relating N_A, Avogadro's number, to the viscosity and diffusion coefficient of a liquid with suspended particles. The second relation, the Einstein–Smoluchowski relation, also allowed N_A to be deduced from measurement in the Brownian motion (Chapter 2). Finally, from the blackbody radiation spectrum (Section 4.1.1) one could deduce, besides Planck's constant, also the Boltzmann constant $k_B = 1.380 \times 10^{-23}$ J K^{-1}, which led directly to $N_A = R/k_B = 6.02 \times 10^{23}$/mol, because the gas constant $R = 8.314$ J K^{-1}/mol was already known.
2. Even though Einstein conjectured that the motion he predicted in his 1905c paper, as discussed in Chapter 2, was the same as Brownian motion, he was prevented from being more definitive because he had no access then to any literature on Brownian motion. He was outside the mainstream academic environment and did not have the research tools typically associated with a university.
3. It is a common misreading of history that had Einstein's derivation of energy quantization in his 1905 study of blackbody radiation as a direct extension of Planck's work on the same problem in 1900. In fact Einstein's derivation of energy quantization was different from that of Planck's, and was by an approach that was, from the viewpoint of the then accepted physics, less problematic. But the important difference between Einstein and Planck was that Einstein, through his derivation by way of the equipartition theorem of the Rayleigh–Jeans law, was the first one to understand clearly the challenge that blackbody radiation posed for classical physics (cf. Section 4.1). Thus Einstein from the very beginning appreciated the fundamental nature of the break with classical physics this new proposal represented. Planck on the other hand had resisted the new photon idea for more than 10 years after its proposal in 1905 (cf. Chapter 3 and Section 5.1).
4. This can be understood most readily using Einstein's derivation of Planck's distribution law, as given in Section 5.1. Energy quantization implies that the step between energy levels becomes ever greater as the

radiation frequency increases. The Boltzmann factor of $\exp(-E/k_B T)$ would then suppress the ultraviolet contribution.

5. Before Einstein proposed his quantum theory, the success of the equipartition theorem in explaining the pattern of specific heat was very much confused. For instance, why the vibrational degrees of freedom must be ignored in the case of gases while they are the dominant components in solids. This led many to question the whole idea of the molecular composition of matter, as the counting of their degrees of freedom did not seem to match the observed result. See Section 5.2.
6. A field obeys a wave equation and its solution can be viewed as a collection of oscillators (Section 3.1). A quantum field is a collection of quantum oscillators. In the quantum mechanical treatment, the dynamical variables of oscillators are taken to be noncommuting operators, leading to the particle features of the system. The raising and lowering operators in the quantum formalism provide the natural language for the description of emission and absorption of radiation, and more generally, for the description of particle creation and annihilation. The surprising result of wave–particle duality discovered by Einstein in his study of fluctuations of radiation energy found its natural resolution in quantum field theory, when the fluctuation was calculated for these quantized waves with noncommuting field operators. More details are provided in Section 6.4.
7. Einstein advocated the local realist viewpoint that an object had definite attributes whether they had been measured or not. The orthodox interpretation of quantum mechanics (that measurement actually produces an object's properties) would imply that the measurement of one part of an entangled quantum state can instantaneously produce the value of another part, no matter how far these two parts have been separated. Einstein's criticism shone a light on this 'spooky action-at-a-distance' feature; its discussion and debate have illuminated the meaning of quantum mechanics. It led later to Bell's theorem showing that these seemingly philosophical questions could lead to observable results. The experimental vindication of the orthodox theory has sharpened our appreciation of the nonlocal features of quantum mechanics. Nevertheless, the counter-intuitive QM picture of objective reality still troubles many, leaving one to wonder whether quantum mechanics is ultimately a complete theory (Chapter 8).
8. The key idea of Einstein's special relativity is the new conception of time. Time, just like space, becomes a coordinate-dependent quantity. This, when augmented by the postulate of the constancy of light velocity, leads directly to the Lorentz transformation as the coordinate transformation among inertial frames of reference. This is in contrast to Lorentz's derivation based on a model of the aether–light interaction. While Einstein's derivation in this new kinematics implied its applicability to all of physics, Lorentz's specific dynamical theory, even if it were correct, was restricted to electrodynamics only (Section 10.3.1 and the final three sections of Chapter 9).
9. Stellar aberration, Fizeau's experiment, and Fresnel's formula can be viewed as lending important experimental support to what Einstein

needed in proposing a coordinate-dependent time—the key element of special relativity. See our discussion, in Sections 9.3 and 9.4, of their relations to Lorentz's 'local time'. Their straightforward derivation from special relativity is given in Section 10.6.

10. To obtain the length of an object one must find the positions of the front and the back of the object. The relativity of time comes into play in these two measurements. See Section 10.1.3.
11. Special relativity is 'special' because it restricts the invariance of physics laws to a special set of coordinate systems: the inertial frames of reference (Section 9.1), while general relativity allows all coordinate frames. Special relativity is not applicable to gravity because the concept of 'inertial frames' becomes meaningless in the presence of gravity (Section 12.2). The general theory of relativity is automatically a theory of gravitation because, according to the equivalence principle, any accelerated frame can be regarded as an inertial frame with gravity. General relativity in an 'interaction-free situation' is a theory of pure gravity; the GR version of any other interaction, say, electrodynamics, is the theory of that interaction in the presence of a gravitational field. See the introduction and final remarks in Section 13.4.
12. Although Minkowski's geometric formulation is a mathematical language that did not immediately lead to any new physical results in special relativity, it nevertheless supplies the framework in which the symmetry between space and time can be implemented in an elegant way. Einstein finally became appreciative of such a language when he realized that it provided him with just the avenue to extend special to general relativity. Einstein's greatest ability lay in his extraordinary physical instinct. It took him some time to truly value the connection between mathematics and new physics theory: some theoretical physics insights came about only when the necessary mathematical languages were available to facilitate such advances. The formulation of general relativity in the framework of Riemannian geometry is of course a glorious example. In this case Einstein was fortunate to have the assistance of his mathematician friend Marcel Grossmann. Still, Einstein had to struggle a great deal and, very much to his credit, he was finally able to find the correct GR field equation. We may speculate on the reason why Einstein was less successful in his unified field theory program. Besides his failure to take note of the new discoveries of the weak and strong forces as new fundamental interactions, he could possibly have made more progress had he been as great a mathematician as he was a great physicist. In this connection we have in mind the case of Newton who formulated his new theory of mechanics and gravitation that was greatly facilitated by his concurrent invention of calculus. See the discussion in Sections 11.1, 14.3.4, and 17.4.2.
13. The realization that gravity can be transformed away in a coordinate frame in free fall was called by Einstein 'my happiest thought'. It became the basis of the principle of equivalence between inertia and gravitation, which was used by Einstein as the handle to extend special to general relativity (Section 12.2.2). The moment of elation when Einstein found

out, in mid-November 1915, that he could correctly explain, from first principles in his new gravitational theory, the observed precession of the planet Mercury's orbit (Section 14.5.1) was, according to Pais, 'the strongest emotional experience in Einstein's scientific life'.

14. By a geometric theory, or a geometric description, of any physical phenomenon, we mean that the results of physical measurements can be attributed directly to the underlying geometry of space and time. Einstein started by studying the generalization of the equivalence between inertia and gravitation (first observed as the equality between inertial and gravitational masses) to electromagnetism. He showed that such a 'strong equivalence principle' implied a gravitational frequency shift, gravitational time dilation, and gravitational bending of a light ray (see Section 12.3). Such considerations led Einstein to the idea that the gravitational effect on a body can be attributed directly to some underlying spacetime feature. Thus, gravitational time dilation could be interpreted as the warping of spacetime in the time direction; a disk in a rotationally symmetric gravitational field has a non-Euclidean relation between its circumference and its radius, etc. (cf. Sections 13.1 and 13.2). In this way these partial GR results suggested to Einstein that 'a gravitational field is simply spacetime with curvature'. Such a description is clearly compatible with the EP result that any gravitational field can be transformed away locally, just as any curved space is locally flat. To what physical realm does Einstein's theory extend Newtonian gravity? It can be demonstrated that the GR equations, whether its equation of motion (the geodesic equation) or its field equation (the Einstein equation), reduce to their corresponding parts in the Newtonian theory when one takes the 'Newtonian limit': when particles move with nonrelativistic speed in a weak and static gravitational field. See Sections 13.2.2 and 14.4.1. This means that GR extends Newtonian gravity to the realm of a time-dependent gravitation field which is strong and allows for particles moving close to the speed of light.
15. The GR field equation, the Einstein equation, can be written as an equality between the spacetime curvature (the Einstein tensor) on the geometry side and the energy–momentum–stress tensor on the energy–matter side. The curvature being the nonlinear second derivatives of the metric, which is interpreted as the relativistic gravitational potential, is the relativistic version of the familiar tidal forces (Sections 14.3 and 14.4).
16. The observed changing rotation rate of the Hulse–Taylor binary pulsar system was found to be in agreement with the GR prediction over a time period of more than two decades (see Fig. 14.2 in Section 14.4.2).
17. The structure of the Schwarzschild spacetime is such that its metric elements

$$g_{00} = -\frac{1}{g_{rr}} = -\left(1 - \frac{r^*}{r}\right),$$

change sign when the radial distance r moves across the Schwarzschild radius r^*. In this way the various spacetime intervals ds^2 change from being space-like to time-like, and vice versa (cf. Section 11.3). This means a time-like or light-like worldline (as traced out by a material particle or a light ray), which always moves in the direction of ever increasing time when outside the black hole ($r > r^*$), once it crosses the event horizon (to the $r < r^*$ region), will be forced to move in the direction of $r = 0$. Pictorially we can represent this as 'lightcones tipping over across the $r = r^*$ horizon'. We say such features demonstrate the full power and glory of general relativity: Relativity requires space and time to be treated on an equal footing—as is best done by taking spacetime as the physics arena. In special relativity the spacetime geometry is still flat, while general relativity involves a warped spacetime. In the case of a black hole when the radial size r is comparable to r^* the warpage of spacetime is so severe that the roles of space and time can be switched (Sections 11.3 and 14.5).

18. Each of these fundamental constants can be viewed as the 'conversion factor' that connects disparate realms of physics: Planck's constant h connects waves to particles; the light velocity c, between space and time; and Newton's constant G_{N}, between geometry and matter/energy. Einstein made pivotal contributions to all these connections through his discoveries in quantum theory, and special and general relativity (Sections 3.4.2, 6.1, 11.4, 14.4, and also 17.1.1).
19. As recounted in George Gamow's brief autography, *My Worldline*, Einstein apparently told Gamow that his introduction of the cosmological constant was 'the biggest blunder of my life'. But we now regard Einstein's discovery of this gravitational repulsion term Λ as a great contribution to modern cosmology: Λ is the crucial ingredient of inflationary cosmology, describing the explosive beginning of the universe, and in the present cosmic epoch, it is the 'dark energy' that constitutes 75% of the cosmic energy content and causes the universe's expansion to accelerate (Section 15.3).
20. The claim that Einstein's idea was of paramount importance in the successful creation of the Standard Model of particle physics is based on the fact that his teaching on the importance of symmetry principles in physics gave us the framework to understand particle interactions. Especially, the whole idea of gauge symmetry grew from the idea of spacetime-dependent transformations in the general theory of relativity. The Standard Model shows that all the principal fundamental interactions: electrodynamics, weak and strong interactions, are gauge interactions (Chapter 16, especially Sections 16.1 and 16.5.5).
21. The driving force behind Einstein's 20-year effort in the unified field theory program was his hope that such a unification would shed light on the quantum mystery. His motivation for new physics was often prompted by the promise of wider comprehension that a new synthesis would bring. While Einstein was not ultimately successful in this effort, his pursuit has inspired the research of others in this direction. In Chapter 17 we present the Kaluza–Klein (KK) theory as a shining example of Einstein's unification program. It not only unifies gravitation with electrodynamics in a GR theory with a 5D spacetime, but also suggests a possible interpretation of the internal charge space and gauge symmetry as reflecting the

existence of a compactified extra spatial dimension. On the other hand, the KK theory did not shed light on the origin of quantum mechanics; in fact it incorporates quantum field theory in order to have a self-consistent description. Nevertheless, the effort to incorporate quantum mechanics, in the form of the Standard Model, with gravity, in the form of general relativity, is a major forefront of modern theoretical physics research.