Fundamental Physics, Partial Models* and Time's Arrow

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Abstract

This paper explores the scientific viability of the concept of causality—by questioning a central element of the distinction between "fundamental" and non-fundamental physics. It will be argued that the prevalent emphasis on fundamental physics involves formalistic and idealized partial models of physical regularities abstracting from and idealizing the causal evolution of physical systems. The accepted roles of partial models and of the special sciences in the growth of knowledge help demonstrate proper limitations of the concept of fundamental physics. We expect that a cause precedes its effect. But in some tension with this point, fundamental physical law is often held to be symmetrical and all-encompassing. Physical time, however, has not only measurable extension, as with spatial dimensions, it also has a direction—from the past through the present into the future. This preferred direction is time's arrow. In spite of this standard contrast of time with space, if all the fundamental laws of physics are symmetrical, they are indifferent to time's arrow. In consequence, excessive emphasis on the ideal of symmetrical, fundamental laws of physics generates skepticism regarding the common-sense and scientific uses of the concept of causality. The expectation has been that all physical phenomena are capable of explanation and prediction by reference to fundamental physicals laws—so that the laws and phenomena of statistical thermodynamics—and of the special sciences—must be derivative and/or secondary. The most important and oft repeated explanation of time's arrow, however, is provided by the second law of thermodynamics. This paper explores the prospects for time's arrow based on the second law. The concept of causality employed here is empirically based, though acknowledging practical scientific interests, and is linked to time's arrow and to the thesis that there can be no causal change, in any domain of inquiry, without physical interaction.

I. Temporal symmetry and fundamental physics

It is prevalently held that the fundamental or primary laws of physics are symmetric in time and all-encompassing.[1] Part of the plausibility of this under-

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1. See, e.g., Davies, Paul 1977, *The Physics of Time Asymmetry*, p. 26, who puts it this way: "All known laws of physics are invariant under time reversal,"—though noting the singular exception of processes involving K-mesons and the weak force. Cf. Greene, Brian 2004, *The Fabric of the Cosmos*, p. 145: "…not only do known laws fail to tells us why we see

standing of physical law depends on the relationship of physics to the special sciences. There is a plausible sense in which physics is *fundamental* in relation to the special sciences. If exceptions are found to laws or generalizations of the special sciences such as psychology, biology or chemistry, then one reasonably seeks explanation in more basic or underlying scientific laws or generalizations. Psychology may reasonably seek answers to some of its problems in physiology or neurology, biology may look to biochemistry, and chemistry may look to physics, etc.

But in physics the pursuit of underlying explanatory factors or mechanism comes to an end, in the sense that there is no more basic natural science which provides needed explanations or understanding of anomalies or exceptions in physics.[2] I see little ground to question the thesis. This is quite different, however, from the claim that the special sciences are somehow incomplete or defective until and unless they are fully explained by or reduced to details of physics.

Nobel Prize winning physicist, Steven Weinberg, emphasized a related point in his 1992 book, *Dreams of a Final Theory*:

> When we say that one truth explains another, as for instance that the physical principles (the rules of quantum mechanics) governing electrons in electric fields explain the laws of chemistry, we do not necessarily mean that we can actually deduce the truths we claim have been explained. Sometimes we can complete the deduction, as for the chemistry of the very simple hydrogen molecule. But sometimes the problem is just too complicated for us. In speaking in this way of scientific explanations, we have in mind not what scientists actually deduce but instead a necessity built into nature itself.[3]

The sense in which quantum mechanics explains laws of chemistry involves a kind of *projection* from simple cases, where the relationship is clear, to more complex cases, where the actual deduction of chemical laws or properties of complex atoms and molecules is impractical. One reason that chemistry persists in its special modes of understanding and explanation, instead of simply substituting physics, is that the required physics is not fully suited to the complexities; and, in effect, as Weinberg has it, "sometimes the problem is just too complicated for us." Still, where anomalies or exceptions to chemical laws appear, one expects that study of the relevant physics might be very helpful. While generally sympathetic to what Weinberg says in this passage, I would emphasize, too, the small contrast I introduced between thinking of this as a matter of reasonable scientific *projection* and Weinberg's talk of a "necessity built into nature itself." Projections from a well understood model can be more or less reasonable, given the state of scientific knowledge, but talk of necessities of nature resists the gradation.

Within physics, there is a prevalent view that various laws, particles or physical constants are more basic, fundamental, primary or foundational,

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events unfold in only one order, they also tell us that, in theory, events can unfold in reverse order."

2. Cf. e.g., Fodor, J.A. 1974, "Special Sciences," *Synthèse*, Vol. 28, pp. 77-115. Reprinted in Fodor 1981, *RePresentations*, pp. 127-45, "all events that fall under the laws of any science are physical events and hence fall under the laws of physics."
3. Weinberg, Steven 1992, *Dreams of a Final Theory*, p. 9.

usually in the sense that they play a central role in explaining and ordering a wide range of physical or scientific generalizations. This idea is reflected, for example, in detailed accounts of the fundamental particles of the Standard Model of particle physics.[4] But it is sometimes explicitly held that the fundamental particles of the Standard Model are simply those which are, as yet, not subject to further analysis or explanation. A powerful particle collider, such as the LHC at Geneva, provides energy sufficient to detect quarks within the proton and neutron, but no one has yet detected anything smaller within quarks or electrons. It is important to distinguish, then, between holding that some presently accepted generalizations are "fundamental" *in relation* to what is presently known, and saying, on the other hand, that there must be some system of fundamental physics governing all that will ever come to be known.

Temporal symmetry is a matter of the reversibility of physical events and processes in accordance with physical law. The existence of an arrow of time, it has been argued, "is puzzling," because "all basic theories in physics seem to be time symmetric or time reversal invariant."[5] Or, what is sometimes claimed to be equivalent, is that the fundamental physical laws conserve information.[6] Sean Carroll argues, along related lines, that what is crucial is "our ability to reconstruct the past from the present," and "the key concept that ensures reversibility is conservation of information;" if the information needed to specify any state of the world is always preserved, then "we will always be able to run the clock backward and recover any previous state."[7]

Applying fundamental physical laws, e.g., to atoms, molecules, or other bodies, given their present positions and momentum, one could, in principle, equally calculate their future or past positions and momentum. Given the fundamental laws, information concerning physical units of a system at any given time, carries with it implications regarding the system at any other time. As the British astrophysicist, A.S. Eddington concisely put it, speaking to the issue of reversibility, "when the [primary] laws are formulated mathematically," then "there is no more distinction between past and future than between right and left."[8] Though similar views are widely held, I want to suggest that this idea has the ring of excessive idealization.

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4. See, e.g., the brief account in Penrose, Roger 2004, *The Road to Reality*, pp. 627-654; and Carroll, Sean 2012, *The Particle at the End of the Universe*, "Appendix Two, Standard Model Particles," pp. 293-298.
5. Savitt, Steven F. 1995, "Introduction" in Savitt, Steven F. (ed.) *Time's Arrow Today, Recent Physical and Philosophical Work on the Direction of Time*, p. 6.
6. See e.g., Susskind, Leonard 2008, *The Black Hole War*, p. 87: "There is another very subtle law of physics that may be even more fundamental than energy conservation. Its sometimes called reversibility, but let's just call it *information conservation*."
7. Carroll, Sean 2010, *From Eternity to Here*, *The Quest for the Ultimate Theory of Time*, p. 121.
8. Callaway, H.G. ed. 2014, A.S. Eddington, *The Nature of the Physical World*, *An Annotated Edition*, p. 76.

II. Background for Fundamental Physics

In spite of Eddington's appeal to precise mathematical formulation, it seems best for philosophical purposes to follow Einstein and Infield on "fundamental ideas":

> Fundamental ideas play the most essential role in forming a physical theory. Books on physics are full of complicated mathematical formulae. But thought and ideas, not formulae, are the beginning of every physical theory. The ideas must later take the mathematical form of quantitative theory, to make possible the comparison with experiment.[9]

The symmetric, time invariant concept of fundamental physics is rooted, historically, in the interpretation of Newton's laws of motion and his theory of universal gravity. As Einstein put it, writing in 1940, "The first attempt to lay a uniform theoretical foundation was the work of Newton"[10]

> This Newtonian basis proved eminently fruitful and was regarded as final up to the end of the nineteenth century. It not only gave results for the movements of the heavenly bodies, down to the most minute details, but also furnished a theory of the mechanics of discrete and continuous masses, a simple explanation of the principle of the conservation of energy and a complete and brilliant theory of heat. The explanation of the facts of electrodynamics within the Newtonian system was more forced; least convincing of all, from the very beginning, was the theory of light.[11]

Newton's physics eventually gave rise to the "iron determinism" of Laplace's *Philosophical Essay on Probabilities*.[12] According to Laplace, the future is completely determined by the past; and equally, a complete knowledge of the present state of every particle or body completely determines every past configuration. The world is thus a causal "block universe," to use the familiar philosophical term from William James.[13]

Laplace, in an oft quoted passage from his "Essay on Probabilities," provides the following image of the Newtonian world, as viewed by some "immense intelligence":

> We ought to regard the present state of the universe as the effect of its antecedent state and as the cause of the state that is to follow. An intelligence knowing all the forces acting in nature at a given instant, as well as the monetary positions of all things in the universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as the past would be present to its eyes.

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9. Einstein, Albert and Leopold Infield 1938, *The Evolution of Physics*, p. 277.
10. Cf. Einstein, Albert 1940, "Considerations Concerning the Fundamentals of Theoretical Physics," *Science*, vol. 91, No. 2369, p. 488.
11. Einstein 1940, "Considerations," p. 488.
12. Laplace, Pierre-Simon 1820/1902, *A Philosophical Essay on Probabilities,* the Introduction to his *Théorie Analytique des Probabilités*.
13. See James, William 1909/2008, *A Pluralistic Universe*, p. 47, in the 2008 edition: "Every single event is ultimately related to every other, and determined by the whole to which it belongs." In James' general conception of the block universe, the determination need not be causal.

> The perfection that the human mind has been able to give to astronomy affords but a feeble outline of such an intelligence.[14]

For this imagined and vastly powerful intelligence, which came to be called “Laplace’s demon,” nothing would be uncertain, “the future as the past would be present to its eyes.” This is a powerful philosophical image of a world of mechanical, deterministic causation, as nearly comprehensive as the medieval philosophical image of *atemporal* Divine omniscience.[15]

Writing in the late 1920’s near the end of the period which saw the intensive development of the twentieth century’s two great revolutions in physics, relativity and quantum mechanics, Eddington posed the question and expressed some doubts regarding the comprehensive character of “primary law.”

> I have called the laws controlling the behavior of single individuals “primary laws,” implying that the second law of thermodynamics, although a recognized law of Nature, is in some sense a secondary law. This distinction can now be placed on a regular footing. Some things never happen in the physical world because they are *impossible*; others because they are *too improbable*. The laws which forbid the first are the primary laws; the laws which forbid the second are the secondary laws. It has been the conviction of nearly all physicists[16] that at the root of everything there is a complete scheme of primary law governing the career of every particle or constituent of the world with an iron determinism. This primary scheme is all-sufficing, for, since it fixes the history of every constituent of the world, it fixes the whole world-history.[17]

Eddington’s doubts concerning “iron determinism” and the “conviction of nearly all physicists,” are directly connected with the status of the second law of thermodynamics. In any closed system, entropy, understood as a measure of the disorder of physical systems, tends to increase. That is to say that the usable energy, suited or configured to perform work *decreases*. Time’s arrow follows a statistical order of development—from less probable, but more orderly configurations toward more probable and less orderly configurations. If the second law, telling us that entropy in a closed system always increases (or at best remains constant) is demoted to “secondary” status, and thought of, say, as a practical means of keeping track of developments on larger scales, when the micro-scale details of particles and motions are too complex, then time’s arrow, as tracked by the second law, suffers a similar demotion.

On a deeper level, though, the question may be posed of the relationship between the statistical character of the second law and the probabilistic character of quantum mechanics—according to which physical chance is basic. In spite of this possible basis, the idea of a system of “fundamental” or primary

14. Laplace 1820/1902, p. 4.
15. Contrast Lloyd, Seth 2006, *Programming the Universe*, p. 98: “Even if the underlying laws of physics were fully deterministic, however, … to perform the type of simulation Laplace envisaged, the calculating demon would have to have at least as much computational power as the universe as a whole.” This is to suggest that the required computation is physically impossible.
16. Eddington’s note: “There are, however, others beside myself who have recently begun to question it.” See Eddington 2014, p. 85, fn 1.
17. Eddington 2014, p. 85.

and time symmetric physical law has often, even chiefly, survived the challenge posed to it by quantum mechanics and by Heisenberg's uncertainty principle.

To see why this is, we may return to Einstein's related views. Taking into account the varieties of science, focused on more limited domains and closer to human experience, Einstein has it that "from the very beginning there has always been present the attempt to find a unifying theoretical basis for all the single sciences…"[18] Such a "unifying theoretical basis," as he sees it, consists

> …of a minimum of concepts and fundamental relationships, from which all the concepts and relationships of the single disciplines might be derived by logical process. This is what we mean by a search for a foundation of the whole of physics. The confident belief that this ultimate goal may be reached is the chief source of the passionate devotion which has always animated the researcher.[19]

On this approach, fundamental physics aims to encompass all the concepts and laws required for ideal comprehension and unification of scientific results, including all more specialize and practical sub-disciplines; and there is clearly a strong suggestion here of logical reduction of the "whole of physics" to the "fundamental concepts and relationships." To use the literary term, it is very much a matter of searching for thematic unity—of a strictly logical and explanatory sort.

To the end of his life, Einstein worked at a "unified field theory," which would be a comprehensive fundamental theory, unifying the gravitational field of his theory of general relativity, with the theory of the electromagnetic field, starting from Maxwell's equations. It was a desideratum of this program that it would ultimately account for quantum mechanics as correct so far as it went, but non-fundamental.[20] He remained convinced of the "incompleteness" of quantum mechanics, with its intrinsic chance, "quantum jumps," super-positions and non-local quantum entanglements.[21] Einstein's projection of a preferred direction of the development of fundamental physics, however, came into conflict with the actual, historical course of its development. Taking that lesson seriously, one will also understand the tendency to identify "fundamental Physics" with investigation of the open problems arising from its best established theories.[22] The best laid plans of mice and men often go astray, and so it is with the best laid scientific projections of fundamental physics.

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18. Einstein 1940, "Considerations," p. 488.
19. Einstein 1940, "Considerations," p. 488.
20. Cf. Sauer, T. 2014, "Einstein's Unified Field Theory Program," in Jannsen, Michel and Christoph Lehner eds, 2014, *The Cambridge Companion to Einstein*, p. 287.
21. See, e.g., the very influential "EPR paper:" Einstein, Albert, P. Podolsky, and N. Rosen 1935, "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?" *Physical Review* 47, pp. 777-780.
22. See, for instance, Hewett, J.L., H. Weets et al. 2012, *Fundamental Physics at the Intensity Frontier, Report of the Workshop held December 2011 in Rockville, MD*. SLAC National Accelerator Laboratory, Stanford University. The editors of the volume comment that the Standard Model of particles physics "leaves some big questions unanswered;" Some of these questions "are within the Standard Model itself," such as "why there are so many fundamental particles and why they have different masses;" and "In other cases, the Standard Model simply fails to explain some phenomena, such as the observed matter-antimatter asymmetry in the universe, the existence of dark matter and dark energy, and the mechanism that reconciles gravity with quantum mechanics." If what is regarded as

Einstein's doubts concerning quantum theory are usually viewed as obsolete. Heisenberg's uncertainty principle is taken to supersede Newtonian, Laplacean or Einsteinian determinism, since there is a fundamental uncertainty in the positions and velocities of the basic constituents of the universe. Few are the contemporary physicists who would try to remove the uncertainty relation from physics. Yet, this is not the end of the story, since there is also a quantum conception of determinism, arising from the uniform evolution of the Schrödinger equation and its derivatives. As Brian Greene has put the point, "Knowledge of the wave functions of all of the fundamental ingredients of the universe at some moment in time allows a "vast enough" intelligence to determine the wave functions at any prior or future time."[23] The point shifts determinism from the calculation of outcomes of physical interactions to the calculation of the probabilities for groups of outcomes, while the quantum uncertainty of prediction and measurement of individual results is retained. Whether determinism belongs to fundamental physics comes, in this way, to depend on the emphasis placed on calculation of probabilities vs. the uncertainty of particular measurements.

III. Models in physics and the concept of the graviton

The general wave-particle duality of quantum mechanics and quantum field theory encourages postulation of the graviton, conceived in analogy to the photon as the carrier of the gravitational force. In accordance with hypotheses directly quantizing the gravitational field, the graviton would be a spin2 particle of zero mass and zero electrical charge, traveling at the speed of light. Wave-particle duality is formalized in contemporary physics, telling us that particle momentum p is equal to the Planck constant h divided by wavelength λ.

$$p = h/\lambda$$

This formula draws on Einstein's work on the photoelectric effect, the equivalence of mass and energy, and de Broglie's hypothesis of matter waves. Thus, to extend the argument, if there are gravitational waves, of a given wavelength, then there will be corresponding particles, analogous to photons—of zero mass and very small momentum. In Einstein's general theory of relativity, information is never transmitted faster than the speed of light, and on some models of quantum gravity, the graviton is wanted to carry information concerning changing positions of masses and the associated gravitational fields at finite speed and over unlimited range. In effect, the hypothesis formulated in quantum field theory is that masses interact gravitationally by exchange of gravitons.

However, the hypothesis of gravitational waves enjoys much firmer support. Gravitational waves are a prediction of general relativity on most prominent accounts.[24] General relativity has been confirmed in repeated and varied empiri-

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"fundamental" is viewed as open to question and inquiry, then the concept is much less problematic.

23. Greene, Brian 2000, *The Elegant Universe*, p. 341.
24. See, for instance Weinberg, Steven 1977/1988, *The First Three Minuets*, p. 147-148: "Gravitational radiation interacts far more weakly with matter than electromagnetic radiation, or even neutrinos" and he continues, "For this reason, although we are reasonably confident on theoretical grounds of the existence of gravitational radiation, the most strenu-

cal tests for nearly a century. Though gravitational waves have not been detected, as of yet (early 2015), they are firmly expected as a further confirmation of general relativity. Much time, money and effort has been expended on the construction and calibration of sensitive detection devices, such as LIGO (the Laser Interferometer Gravitational Wave Observatory).[25] Following Einstein, gravitational waves are an expected effect of accelerating masses, in analogy with how electromagnetic waves are created by moving charges. Yet gravity is the weakest of the four fundamental forces of nature by many orders of magnitude, and in consequence, the displacements that physicists can expect to measure with instruments such as LIGO, as the signals of passing gravitational waves, are extremely small—on the order of 10^{-18} meters, which is 1000 times smaller than the diameter of a single proton.[26] The experimental design depends on reflecting light along two long tracks, set at right angles to each other, and bringing the beams of light back, via mirrors, to a central point where interference can be detected, indicating a slight change in length of one of the two paths.

One expected source of gravitational waves are pairs of small and extremely dense neutron stars in mutual orbit, or again, pairs of black holes spiraling in toward each other and their eventual fusion. Important observational results have shown that identified binary pulsars do in fact lose energy, as they spiral inward, consistent with the prediction from general relativity of their loss of energy by emission of gravitational waves. Astrophysicists Joseph Taylor and Russell Hulse were awarded the Nobel prize for their related work, using the timing of a pulsar as a precise clock, allowing a measurements, over decades, of the predicted energy loss.[27]

The prospect of detecting gravitons, in contrast, is extremely dim.[28] The point has been emphasized in writings of Freeman Dyson, and I quote from the *defenders* of the detection of gravitons. In comparison with the prospects of detecting gravitational waves,

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ous efforts have so far apparently failed to detect gravitational waves from any source." On the history of the decades long theoretical debate, including Einstein's own occasional doubts, see Kennefick, Daniel 2007, *Traveling at the Speed of Thought*. Approximate solutions of the Einstein equations predicting gravitational waves date to Einstein 1916, "Nährungsweise Integration der Feldgleichungen der Gravitation." See Einstein 1916, "Approximative Integration of the Field Equations of Gravitation," in Einstein 1997, *The Collected Papers of Albert Einstein*, Vol. 6, The Berlin Years, pp. 201-210.

25. The LIGO project, with major facilities in Louisiana and Washington State, is the largest scientific project ever funded by the U.S. National Science Foundation, to the tune of over $300 million in capital investment and $30 million per year, since the early 1990s.
26. See "Introduction to LIGO and Gravitational Waves," at the LIGO web pages.
27. See e.g., Taylor's Nobel Lecture, describing his work, 1997, "Binary Pulsars and Relativistic Gravity." The observed loss of energy is consistent with the generation of gravitational waves, in accordance with solutions of the Einstein field equations.
28. See Dyson, Freeman 2012, "Is a Graviton Detectable?" (his Poincaré Prize Lecture). See also Dyson's review of Brian Greene's *The Fabric of the Cosmos*, in *The New York Review of Books*, May 13, 2004. On the prospect of detection of gravitons in a particle collider, Sean Carroll writes, "Gravitons are only produced by gravitational interaction, which is so weak that essentially no gravitons are made in a collider and we don't have to worry about them." See Carroll 2012, *The Particle at the End of the Universe*, p. 104-105.

> The possibility of detecting individual gravitons is far more daunting. Indeed Freeman Dyson and colleagues have cogently estimated that it may in fact be infinitely more daunting, namely that it is likely to be impossible to physically realize a detector sensitive to individual gravitons without having the detector collapse into a black hole in the process.[29]

Though both general relativity and quantum field theory are regularly counted to fundamental physics, the graviton does not appear in general relativity or in the Standard Model of particle physics—which does not encompass gravitation. The graviton is instead a postulate which appears in projecting the quantum field theory used in the Standard Model in the hope of unifying its three forces—the electromagnetic force, the strong nuclear force and the weak force—with gravity. A chief point of interest in this, for present purposes, is to understand the contrast of theoretical standing between the use of the word "model" in the description of the Standard Model of particle physics, and the idea of including the graviton in a more comprehensive model.

The standard model of particle physics is admittedly incomplete, since it does not encompass gravity. Beyond that, it is generally recognized that most of the matter in the universe (so-called "dark matter") takes forms outside the standard model.[30] Yet the standard model is also extremely well supported by experimental evidence, and the recent detection of the Higgs boson at CERN counts as further confirmation. To speak of "the Standard *Model*," as a model, is somewhat concessionary, in light of its strong empirical support—with an eye to its incompleteness. In a similar way, general relativity has met every test to which it has been subjected, though the lack of integration of GR with quantum mechanics leaves room for new physics. However, the models of new physics which include the graviton, are more theoretical and even speculative; and very little supporting evidence is available. Weinberg writes:

> Because string theories incorporate gravitons and a host of other particles, they provide for the first time the basis for a possible final theory. Indeed, because a graviton seems to be an unavoidable feature of any string theory, one can say that string theory explains why gravitons exist.[31]

But this is a very weak sense of explanation and more a matter of a theoretical, explanatory proposal. String theory predicts the existence of the graviton, as we may understand Weinberg to claim, and *would* explain the graviton, if string theory were sufficiently supported as a "final theory."

While the Standard Model of particle physics and general relativity each belong to more settled "fundamental physics," models including the graviton are more speculative theoretical projections or possible additions to fundamental physics. They are invoked in particular proposals concerning quantum gravity, or the problem of how to integrate general relativity with quantum mechanics; and they treat of quantum field theory as something to be preserved

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29. Krausss, L.M. and F. Wilczek 2014, "Using Cosmology to Establish the Quantization of Gravity," *Physical Review* D, 89, No. 4. See also Rothman, T. and S. Boughn 2006, "Can Gravitons be Detected?" *Foundations of Physics* 36, pp. 1801-1825
30. See e.g., Carroll, Sean 2010, *From Eternity to Here,* p. 389: "…there must be dark matter, and we have ruled out all known particles as candidates… ."
31. Weinberg 1992, *Dreams*, p. 216.

at certain limits, as "effective quantum field theory" and extended to gravitation. Yet models strongly committed to postulating the graviton are only some among a variety of theoretical approaches to the tensions between general relativity and quantum mechanics.[32] As a general matter, Dyson's problem of detecting the graviton reflects the incompatibilities between GR and QFT, centered on the background metric assumed in QFT vs. the background independence of GR and the dim prospect of any physical probing of the Planck length. The physical energies required to probe structures at the scale of the Planck length of 10^{-33} cm are so great that they would disrupt the physical geometry of the structures under study.[33] The point casts some doubt on the approach to quantum gravity based on string theory and QFT and opens the door to approaches to quantum gravity based in background independent, non-commutative geometry. From this perspective, even the well-confirmed Standard Model of particle physics, in spite of its considerable strides and impressive empirical support, is one among possible alternative models for new physics beyond.

IV. Quantum indeterminacy and temporal symmetry

Newtonian mechanics, Maxwell's theory of electromagnetism, and Einstein's revisions of Newtonian theory in special and general relativity count as fully deterministic, in accordance with the claimed temporal symmetry of fundamental physics; but there is also historical and contemporary interest in the challenge represented by the Heisenberg uncertainty principle and the chance or probabilistic element in quantum mechanics. This stands in tension with the strong contrary tendency to think of quantum theory in terms of the uniform evolution of the wave function of the Schrödinger equation and to discount the cogency of indeterministic "quantum state reduction" or the "collapse of the wave function." This is one way in which the thesis of temporal symmetry enters into the complex of issues connected with the interpretation of quantum mechanics.

Regarding the chance element in contemporary physics, we need to ask whether chance will be fully subdued by and assimilated to the uniform evolution of the wave function, or on the contrary, if it might better be regarded as something ramifying through the complexities of the physical world and the wider domains of scientific phenomena. Where isolated, a quantum system evolves in accordance with the Schrödinger equation, which allows for the calculation of probabilities of outcomes of measurements. The other element, however, shows how the state of the system is reduced when an ideal measurement is carried out. While the Schrödinger equation is time reversible, measurement operates only forward in time, and this may be thought of as

32. See e.g. Oriti, Daniele 2009, *Approaches to Quantum Gravity, Toward a New Understanding of Space, Time and Matter*, p. xvi: "I think it is fair to say that we are still far from having constructed a satisfactory theory of quantum gravity, and that any single approach currently being considered is too incomplete or poorly understood, whatever its strength and successes may be, to claim to have achieved its goal, or to have proven to be the only reasonable way to proceed."

33. Cf. the discussion in Majid, Shahn 2008, "Quantum Spacetime and Physical Reality," pp. 67-69.

defining the quantum mechanical arrow of time. But since the Schrödinger equation already determines the probabilities of measured outcomes, via the Born rule, and nothing tells us which outcome will actually be measured on a particular trial, this emphasizes the normal quantum mechanics of the Born rule. To find the probability that the wave function will collapse to a specific state, you take the square of the coefficient of that possible outcome in the Schrödinger equation. The use of the Born rule is empirically adequate, and it does not follow from the Schrödinger equation. In view of these two elements is quantum theory deterministic and temporally symmetric or not?

Amongst the mathematical complexities of the physicists efforts to explain exactly how and why all physical laws are "time-reversal invariant," it seems sometimes to be forgotten that there is a genuine paradox arising from this recurrent motif of fundamental physics. Temporal invariance implies that it is possible, for example, for a tree to shrink down to a shoot and return to the state of a seed, that the old might evolve into younger people and eventually disappear by becoming unborn, or that a dispersion of light could concentrate itself into a narrow beam and return to a flashlight or laser, say. Reverse processes are not frequently observed in nature, though the fundamental laws don't dictate this result. The examples can be multiplied at will, and they represent the physical reality of varieties of unidirectional processes, consistent with our ordinary conception of time pointing from past toward the future. Supposing they are extremely unlikely and not simply impossible, the question persists of *why* they are extremely unlikely. Why does nature favor processes which increase entropy?

It is held by physicist Lorenzo Maccone, in a fascinating short paper, that

> In fact, the laws of physics are time-reversal invariant. Hence there is no preferred direction of time according to which we may establish a *substantial* difference between the two temporal directions past-to-future and future-to-past.[34]

Maccone's intriguing proposal is that though macroscopic reversals of entropy in isolated systems are statistically and therefore physically possible,[35] they leave no evidence—where, as expected, "thermodynamic entropy is a quantity that measures how the usable energy in a physical process is degraded into heat."[36] Avoiding any "substantial" (or fundamental) conception of temporal asymmetry, Maccone also takes the surprising view that "thermodynamic entropy is a subjective quantity," though "for *all practical situations* this is completely irrelevant."[37]

His argument is that there is a hidden assumption build into the various statements of the second law of thermodynamics, to the effect that whenever an isolated system is obtained by combing two theretofore distinguished systems,

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34. Maccone, Lorenzo 2009, "A Quantum Solution to the Arrow of Time Dilemma," arXiv: 0802.0438v3. p. 5; published in *Physical. Review. Letters*. 103.
35. Cf. the discussion in Greene 2004, *The Fabric of the Cosmos*, pp. 159-163. Greene's point is that the purely statistical reasoning of the second law equally suggests that entropy will be found to increase in the *past* of any system considered, since states of higher entropy are generally more probable.
36. Maccone 2009, p. 1.
37. *Ibid*.

"the second law is valid only if the two systems were initially uncorrelated, i.e., if their initial joint entropy is the sum of their individual entropies."[38] But, he holds, it is impossible to know whether a given system is in fact correlated with another in some unknown way, and in consequence, as a practical matter all systems are considered *uncorrelated* without clear evidence to the contrary. Without this assumption, he argues, "it would be impossible to assign an entropy to a system unless the state of the whole universe is known."[39] In spite of the practicality of the second law, then, Maccone's proposals involve a more emphatic version of the distinction between fundamental physics and secondary or derivative law.

The more emphatic character stands out in the general thesis of the article, which states that though "the laws of physics are invariant for time inversion," and "the familiar phenomena of everyday are not," the paradox is solved, according to the argument of the paper, since it argues that "phenomenon where entropy decreases" will fail to "leave any information of their having happened," and this situation "is completely indistinguishable from their not having happened at all."[40]

The position is remarkable, since it preserves temporal invariance by placing any evidence of processes of decreasing entropy beyond possible observation, and in consequence, the second law of thermodynamics, according to Maccone, is reduced to a "tautology." This is a strong claim, and one may easily suppose to the contrary that reverse processes may be observed—at least under simplified experimental conditions.

Without considering Maccone's central argument, which is based on the physical possibility of reverse processes resulting in decreasing entropy (greater free energy), his position illustrates just how far physicists are willing to go to preserve the claimed symmetry or temporal invariance of fundamental physics. It is a concise and fascinating little paper, and I only aim to suggest doubts about its conclusion. That we do not (or do not frequently) observe macroscopic temporal reversals of physical processes (in closed systems) seems a point too physically significant to want to explain away. The specifics of Maccone's thought experiment are impossible in practice, since it involves control at the quantum level of the results of the forward process, and subsequent erasure of all evidence of it. Part of the interest of the paper is that it rests on an equivalence of quantum processes with information.

Turning to a more prominent view of the relationship between fundamental physics and quantum indeterminacy, I want to briefly consider Brian Greene's discussions of the arrow of time, and in particular, "Time and the Quantum," Chapter 7, of his 2004 book. This is a fine exposition of the related questions, posed in terms open to the broad, educated public. Greene defends the deterministic, temporal-symmetry orthodoxy. His question in the chapter is "whether there is a temporal arrow in the quantum mechanical description of nature."[41] His conclusion reaffirms temporal invariance of fundamental law, including

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38. *Ibid*.
39. *Ibid*.
40. *Ibid*.
41. Greene 2004, p. 177.

quantum mechanics, and links the arrow of time to the surprisingly low entropy of the initial condition of the universe, subsequent to the big bang—invoking a cosmological arrow of time. However, while the cosmological arrow of time is widely accepted, it too seems to require explanation.

Greene's provides a concise overview of the theme of quantum decoherence, together with an equally concise overview of the "quantum measurement problem," and his question is posed within this rich theoretical context. In general terms, approaches to the interpretation of quantum mechanics via quantum decoherence can be viewed as a contemporary up-date and revision of a controversial element of the "Copenhagen interpretation" developed, early on by Niels Bohr, Heisenberg, Max Born and associates. The decoherence approach removes the stress placed on "observation" in earlier accounts of quantum-mechanical phenomena.

The "quantum measurement problem" is something of a mare's nest, a formidable complex of old and new arguments and doubts, including on occasion, a continuing, popular fascination with the idea of a special role of observers in quantum mechanics, Einstein's and Schrödinger's early doubts about the Heisenberg uncertainty principle and the Bohr-Einstein debate,[42] Bohm's hidden variable theory, including, again, doubts on the absence of classical determinism in quantum mechanics, discussions of the Bell inequalities, doubts about Alain Aspect's famous experimental results supporting Bell,[43] the contemporary proposals for "spontaneous collapse,"[44] "multiple worlds" theories in which there is no collapse, and every possible mixture of these issues and themes.

Greene acknowledge the appeal of the decoherence approach in obviating aspects of the quantum measurement problem. The idea is that there is nothing special about observation or measurement. "Human consciousness, human experimenters, and human observations would no longer play a special role since they (we!) would simply be elements of the environment, like air molecules and photons, which can interact with a given physical system."[45] Measurement is, according to the decoherence approach, simply one more interaction of a quantum system with its environment, in which the wavefunction of the system, and the possibility of interference-effects are reduced or modified. Again, "there would no longer be a stage one—stage two split between the

42. See, e.g., Born, Max 1954, the Nobel Lecture, "The Statistical Interpretation of Quantum Mechanics," p. 256.

43. See e.g., the *Journal of Cosmology*, Vols. 3 and 14 on consciousness and the quantum; Bohm, David 1952, "A suggested Interpretation of Quantum Theory in terms of 'Hidden' Variables," I and II. *Physical Review*, 85, pp. 166-193; Bub, Jeffery 2010, "Von Neumann's 'no Hidden Variable' Proof: A Re-Appraisal," *Foundations of Physics* 4, pp. 1333-1340; arXiv:1006.0499v1; Bell, John 1993, *Speakable and Unspeakable in Quantum Mechanics*; Aspect, Alain, P. Grangier and Gerard Roger 1982, "Experimental Realization of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities."

44. Regarding the "spontaneous collapse" proposal of Ghirardi, Rimini and Weber, Brian Greene remarks that "they introduce a collapse mechanism which does have a temporal arrow—an "uncollapsing" wavefunction, one that goes from a spiked to a spread out shape, would not conform to the modified equations." See Greene 2004, p. 214.

45. Greene 2004, p. 212.

evolution of the object and the experimenter who measures them. Everything—observed and observer—would be on an equal footing."[46] There is no need of an *ad hoc*, or physically unmotivated distinction between the quantum world and macroscopic objects or measuring instruments; and the lack of quantum weirdness in the macroscopic world falls out as an effect of environmental decoherence. Experimental detection of interference effects of quantum mechanical systems depends on isolating them and considering very small objects such as photons and electrons, as in the classical double-slit experiments, but these idealized and isolated system are not typical of the complex interactions of real-world happenings: "much as adding tagging devices to the double-slit experiment blurs the resulting wavefunction and thereby washes out interference effects, the constant bombardment of objects by constituents of their environment also washes out the possibility of interference phenomena."[47] On the decoherence approach, there is an answer to the puzzle posed by the thought experiment of Schrödinger's cat, since environmental decoherence would have plausibly taken effect long before any observer looks in on the situation.

I have little doubt that discussions of quantum measurement will continue among the physicists for many years to come, simply in virtue of the complexities involved. So long as the notion lingers that the measurement problem is a matter of getting exact predictions on particular experimental runs, however, and the question takes the form, e.g., "Why doesn't the measurement of a particle in superposition result in a superposition of measurements?"—or, "why does something happen in measurement, not precisely predicted by the Schrödinger equation?"—then I suspect that the physicists will be barking up the wrong tree—where they implicitly put the uncertainty principle in question. As Greene puts the point, "Much in the spirit of Bohr, some physicists believe that searching for such an explanation of how a single, definite outcome arises is misguided." Weinberg's recent proposal is of this general character.[48] "During measurement, " Weinberg says, "the state vector of the microscopic system collapses in a probabilistic way to one of a number of classical states, in a way that is unexplained, and cannot be described by the time-dependent Schrödinger equation." Weinberg's approach avoids the "many worlds" and "hidden variables" views, and, borrowing from decoherence, avoids the classical "Copenhagen" approach as well.

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46. *Ibid*.
47. Greene 2004, p. 210. Cf. Carroll 2010, *From Eternity to Here,* p. 253-254: "In the many-worlds interpretation, decoherence plays a crucial role in the apparent process of wavefunction collapse. The point is not that there is something special or unique about 'consciousness' or 'observers' other than the fact that they are complicated macroscopic objects. The point is that any complicated macroscopic object is inevitably going to be interacting (and therefore entangled) with the outside world, and its hopeless to imagine keeping track of the precise form of the entanglement. For a tiny microscopic system such as an individual electron, we can isolate it and put it into a true quantum superposition, but for a messy system such as a human being … that's just not possible."
48. Greene 2004, p. 213. Cf. Weinberg, Steven 2012, "The Collapse of the State Vector," arXiv:1109.6462v4, p.2: Weinberg proposes a "correction" to quantum mechanics which nonetheless eventuates in "inherently probabilistic collapse" of the state vector, with probabilities given by "the Born rule of ordinary quantum mechanics."

V. Conclusion: Causality and indeterminacy

Causality and indeterminacy are fascinating and widely discussed philosophical topics, and they come together in considering the relationships of quantum indeterminacy and fundamental physics to the arrow of time. Since the arrow appears crucial in ordinary and scientific conceptions of causality, where an effect cannot proceed its cause,[49] it would certainly be of interest to the topic of causality and related debates to find a quantum mechanical arrow in support of a thermodynamic arrow. The most promising candidate for a quantum mechanical arrow of time is to locate it in the inherently probabilistic collapse of the wavefunction. Greene puts the point as follows: "if the resolution of the measurement problem that is one day accepted reveals a fundamental asymmetric treatment of the future versus the past within quantum mechanics," then "it could very well provide the most straightforward explanation of time's arrow."[50] This is not the approach Green most favors, however.

The point shows in Greene's expressed doubts about decoherence. "Even though decoherence suppresses quantum interference and thereby coaxes weird quantum probabilities to be like their familiar classical counterparts," he writes, "each of the potential outcomes embodied in a wavefunction still vies for realization. And so we are left wondering how one outcome 'wins' and where the many other possibilities 'go' when that actually happens."[51]

But, I submit that Greene's first conjunct here is just what we cannot require of an explanation, if the uncertainty principle is true and quantum chance is fundamental. Regarding the Bohm approach, since, according to Greene, equations are needed that show "how a wavefunction pushes a particle around,"[52] and this would apparently require action superseding the speed of light in case of entanglement at astronomical distances, there is significant physical justification for taking quantum indeterminacy flatfootedly.

Will accepting unidirectional state reduction, quantum indeterminacy and a quantum mechanical arrow help in understanding the observed unidirectional increase in entropy in physical processes, and, on that basis, a thermodynamic arrow of time? One idea is that nature favors state reduction toward conditions of increased entropy and that increases of quantum entanglement, due to diverse interaction increase entropy.[53] But Greene is more intent on the cosmological arrow, based on the initial condition of low gravitational entropy in the theory of inflationary expansion. In spite of that, time symmetric laws cannot explain why the observed world has a comparatively low entropy (contrasting the projected heat-death of the universe) or why it had even lower entropy in the past. Moreover, in related approaches, inflationary expansion evokes the

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49. The supposition is that this is true, even if, as sometimes argued, causality is an "emergent" phenomenon. See for instance Norton, John D. 2003, "Causation as Folk Science," p. 1, where the thesis is that though causation is not fundamental, it "remains a most helpful way of conceiving the world."
50. Greene 2004, p. 215.
51. *Ibid*., p. 212.
52. *Ibid*., p. 214.
53. See Lloyd 2006, chapters 4 and 5 on thermodynamics, information and quantum mechanics.

multiverse and emphasis on the "anthropic principle."[54] These are developments which many would like to avoid.

The prospect of finding an explanation of time's arrow within quantum mechanics proper, continues to rest with the Born rule and the idea that in quantum mechanics chance is fundamental. Repeating the same experiment (i.e. the same cause), we get different measurements on different trials. Though resistance to quantum mechanical indeterminacy has sometimes rested on holding onto traditional conceptions of universal causality, fundamental physical support for causality's arrow of time, may ultimately rest on quantum indeterminacy.

The point is somewhat obscured at present, and the obscurity is not unrelated to the role of traditional conceptions of "fundamental physics" in the speculative boom in contemporary physics. This has been stimulated by a number of factors, including the end of the Cold War, the availability of the Large Hadron Collider at CERN, the recent progress of the Standard model, and more basically, the conceptual conflicts between general relativity and quantum mechanics. While there is no contrary evidence to these great twentieth-century paradigms of physics, there has been much theoretical work, of a more speculative character, which aims at models of unification. The possible approaches go off in many diverse directions, though temporal symmetry in fundamental physics is the usual orthodoxy.

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54. Emphasis on the inflationary expansion in the early universe, the multiverse idea and the anthropic principle is even more pronounced in Sean Carroll's recent book, Carroll 2010, *From Eternity to Here*. But see pp. 339-345, where a range of doubts are discussed.

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