Predictability in Science: Accuracy and Limitations
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PREDICTABILITY, DETERMINISM, AND EMERGENCE

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0. Humans are creatures for whom the future is part of present existence, bounded by uncertainty in many respects, but indispensable for comprehending the present. Immanuel Kant views the 'anticipation of the future' as the 'most decisive proof of man's advantage, in that he is able to prepare for remote objectives in keeping with his destiny'.[1] And for Martin Heidegger, the structure of human existence is future oriented in itself.[2] In one sense this holds for ordinary experience, as reflected in anthropological studies, and in yet another sense it holds for science and leads – in connection with the original Greek idea of order in the physical world – to epistemological analysis. In both areas, predictability is the attempt to deal with the future, and in science – for example in the thesis of the structural identity of explanation and prediction – it is also a crucial criterion of a theory. Predictions serve as both an application of a theory and as its confirmation. The following discussion is limited to addressing the problems connecting to these scientific issues.

1. Problems with predictability in science have been discussed for a very long time. This is particularly so for complex relationships. A classic example is the hole in the ozone layer, or, the effects of chlorofluorocarbons (CFCs) on the high atmosphere ozone layer. In this case, the causal relationships of the chemical reactions are so complex that it is almost impossible to predict their effects. After all, it was difficult enough to explain the mere

[1] I. Kant, 'Mutmasslicher Anfang der Menschengeschichte' (1786), in: *Kant's gesammelte Schriften* VIII, Berlin and Leipzig 1923, p. 113 (Engl. 'Conjectures on the Beginning of Human History', in: H. Reiss [ed.], *Kant: Political Writings*, 2nd ed., Cambridge etc. 1991, p. 225).

[2] M. Heidegger, *Sein und Zeit* (1927), 14th ed., Tuebingen 1977, §§ 67ff. ('Zeitlichkeit und Alltaeglichkeit').

occurrence of the effect. Just as well, it is a common fact that small causes can have large, unpredictable effects. Ice ages, for example, according to recent scientific research, are caused by a relatively minor cooling down in the earth's atmosphere. This in turn, is caused by a decreased intensity in the rays of the sun, which results from peculiarities of the earth's revolving around the sun, in particular its varying eccentricity as well as variations in its orientation and the gradient of the earth's axis. The crucial point is that this trifling cooling down leads to a change in flow in the North Atlantic. In particular, the warm flow, which comes to the surface near Iceland and is responsible for the warm climate in Europe, is diverted. This leads to a much harsher climate in the north, which in turn contributes toward cooling at the global dimension.[3] Thus small changes in the conditions cause, in this case, considerable changes in the state of the system as a whole.

Another example is related to Max Planck's (epistemologically problematic) exploration of free will, which has recently become relevant again for brain science. Embarking from the concept of causal universality, i.e. the assumption of causal closure of the world, Planck argues that the will is also causally determined, although mental events, e.g. thoughts, are unpredictable – even for an ideal observer – due to their manifold dependencies. For Planck, this is also relevant for the relations between a willing and a perceiving self (the ideal observer): 'Each new observation (...) gives rise to a new motive, and the recognition of this motive in turn creates a new situation. The series is infinite, and since the observed person (the willing ego) owes no obedience to the observer (the percipient ego), we shall never be able to claim with certainty that the eventual decision must be in the sense of the observer's latest discovery'.[4] This has, following Planck, no bearing on the continued validity of a causal law.

2. On this topic, the most commonly discussed example is chance in quantum mechanics. Quantum mechanics imposes serious limitations on the predictability of events. The central principle of the theory is 'Schroedinger's equation', which serves to determine the 'state function' or 'wave function' of a quantum system. The state function is generally taken to provide a complete description of quantum systems; no properties can

[3] See W.S. Broecker and G.H. Denton, 'Ursachen der Vereisungszyklen', *Spektrum der Wissenschaft* 3, 1990, pp. 88-98.

[4] M. Planck, *Vom Wesen der Willensfreiheit*, 2nd ed., Leipzig 1937, p. 18 (Engl. *The Universe in the Light of Modern Physics*, 2nd ed. [with a section on Free Will], London 1937, p. 101).

be attributed to such a system beyond the ones expressed in terms of the state function. Schroedinger's equation determines the time development of the state function unambiguously. In this sense, quantum mechanics is a *deterministic* theory.

However, apparently irreducible chance elements enter when it comes to predicting the values of observable quantities. The measurement process in quantum mechanics is described as the coupling of the quantum system to a particular measuring apparatus. Schroedinger's equation yields, then, a range of possible measuring values of the quantity in question, each of these values being labelled with a probability estimate. That is, Schroedinger's equation only provides a probability distribution and does not anticipate particular observable events. Quantum mechanics is extended to actual measuring values by adding the so-called 'projection postulate'. This postulate is independent of Schroedinger's equation and says that one of the possible measuring values is assumed in actuality. The spectrum of possible values collapses into the one value that is obtained in the measurement. In repeated measurements of the same kind, the relative frequencies of the values coincide with the probability estimates supplied by Schroedinger's equation.

The salient point is that, according to present lights, this collapse of the state function, i.e., the selection of the actual measuring value from the range of possibilities is a genuinely *indeterministic* process whose outcome cannot be predicted on any basis whatsoever. These obstacles to prediction, as they become manifest in quantum mechanics, have nothing to do with the ignorance of the prevailing initial conditions. Given a complete description of the quantum state, chance fluctuations at the level of observables will yet occur. Quantum mechanics involves in-principle limitations of predictability to the effect that, for instance, it is objectively indeterminate when a given radioactive nucleus will decay. Such limitations are not merely epistemic constraints, but rather represent an ontological indeterminateness.

Heisenberg's so-called indeterminacy relations are a consequence of Schroedinger's equation, although historically they were formulated independent of this equation and prior to its enunciation. The Heisenberg relations place severe limitations on the simultaneous measurement of what is called 'incompatible' or 'incommensurable' quantities like position or momentum or spin values in different directions. The more precise one of the quantities is evaluated, the more room is left for the other one. Like the constraints mentioned before, the limitations set by the Heisenberg relations have nothing to do with practical impediments to increasing measurement accuracy that might overcome by improved techniques. Rather, the relations express limitations set by the laws of nature themselves.

Heisenberg's indeterminacy relations entail serious restrictions of the prediction of future quantum states. For ease of illustration consider the following spin measurements. Spin states are quantized; they possess only two possible values in each direction, namely, 'spin up' or 'spin down'. A beam of electrons can be 'spin-polarized' by sending the particles through a suitably shaped magnetic field (a Stern-Gerlach apparatus). That is, the spin of all electrons in, say, x-direction after exiting from the setup is, say, 'up'. This result can be confirmed by a second measurement of the same quantity performed directly after the first. 100% of the electrons come out 'spin up' in the x-direction. Let the beam then pass through the same setup but now measuring the spin values in the y-direction, perpendicular to x. The outcome is that one half of the beam exhibits 'spin up' and the other half 'spin down'. If the beam is finally sent through the apparatus this time oriented again in x-direction, the perplexing result is that 50% of the electrons are registered 'spin up' and 'spin down', respectively.

Correspondingly, the first measurement, in spite of its quite unambiguous result, cannot be utilized for a prediction once a measurement of an incompatible quantity has been carried out. Again, this is a matter of principle. There is no way of anticipating the joint values of incompatible quantities below the threshold set by the Heisenberg relations. As a result, inherent limitations prevent us from predicting the future states of such quantities.

This element of genuine, irreducible chance troubled Albert Einstein very much. Einstein accepted statistical accounts if they could be viewed as growing out of incomplete knowledge of the relevant conditions and states. Quantum mechanics differed from all other statistical theories in physics in that the invocation of probability could not be attributed to human ignorance. Einstein's commitment to a determinist world was his chief reason for dissenting from quantum mechanics. As he wrote to Max Born, he found the idea 'unbearable' that an electron decides on its own in which direction to move. If this turned out to be true he preferred to be an employee in a gambling casino rather than a physicist.[5] In the same vein, Einstein told Born that quantum mechanics does not bring us closer to God's mystery. After all, God does not throw dice.[6] This episode bears witness to the fact

[5] Einstein to Born (April 29, 1924), in: *Albert Einstein – Hedwig und Max Born: Briefwechsel 1916-1955*, Munich 1969, p. 118.

that in-principle constraints on predictability represent a serious deviation from the notion of *Laplace's demon* which is the core element of the traditional, ignorance-focused account of chance and probability.

To repeat once more: Current wisdom holds there are fundamental processes in the quantum world that inhibit randomness, which implies general limits of predictability. Nevertheless this is by and large irrelevant to macroscopic phenomena; with large numbers of atoms the uncertainties average themselves out. This, in turn, brings us to the fundamental question of the relationship between *determinism* and *predictability*.

3. Talking about the limits of predictability in principle immediately poses questions for a *deterministic world*. This has been clear to Max Planck, leading to the insight that the classical dictum 'an event is causally conditioned, if it can be predicted with certainty'[7] cannot be maintained, moreover, one is forced 'to acknowledge the following sentence as a given fact: In no circumstance is it possible to predict a physical event with exactness'.[8] In a similar vein, several years before (1927), Werner Heisenberg claimed that, 'in principle', quantum mechanics has the effect that, 'the law of causality is in a sense unfounded. Since one can never know precisely the initial conditions, one can never calculate the mechanical course of events. (...) Concerning the sharp version of the law of causality: If we know the present, we can calculate the future – it is not the consequent, but the antecedent that is wrong'.[9] This, however, is not the last word on the possibility of a deterministic world. It is rather necessary to separate the concepts of determinism and predictability from each other; determinism understood here (following J. Earman) as the thesis that, if two possible worlds are identical at a given point in time, then they are identical at every point in time.[10] This does not exclude hindrances to predictability for a given state of affairs and deterministic development. The thesis is: *Even in a*

[6] Einstein to Born (December 4, 1926), *ibid.*, p. 129.

[7] M. Planck, 'Die Kausalität in der Natur' (1932), in: M. Planck, *Vortraege und Erinnerungen*, 5th ed., Stuttgart 1949, p. 252.

[8] *Ibid.*, p. 253.

[9] W. Heisenberg, 'Über die Grundprinzipien der Quantenmechanik', *Forschungen und Fortschritte* 83 (1927), p. 83 (= W. Heisenberg, *Gesammelte Werke / Collected Works*, vol. 1, Munich and Zurich 1984, p. 21).

[10] See J. Earman, *A Primer on Determinism*, Dordrecht etc. 1986, p. 14 ('if two worlds agree for all times on the values of the conditioning magnitudes and if they agree at any instant on the values of the other magnitudes, then they agree at any other instant').

deterministic world there are limits of predictability.

Two reasons can be given in support of this. First, *deterministic chaos*. This refers to the strong dependence of a system's states of affairs on the magnitude of defined parameters. Since the magnitude of these parameters can never be known, the prediction of a system's states of affairs is bound by uncertainty, which translates into a range of different developments in chaotic systems. Unpredictability as a result of chaos is not limited to complex systems, rather, it can also occur in simple systems that only consist of a few elements. For example, two coupled pendulums constitute a simple system, the relevant laws of which have been known for centuries. But it has only recently become clear that, within such an arrangement, in a distinct range of initial conditions – namely system stimulations of medium strength – there can be chaotic and unpredictable oscillations. Another example, already introduced in the beginning, is meteorology, which was the original impulse for studying chaotic effects in dissipative systems. In a well-known metaphor: even the flapping of a butterfly's wings can crucially effect the convection currents in the earth's atmosphere and, hence, meteorological developments ('butterfly effect').[11] The reliability of weather forecasts is not only constrained by *practical* limits but also by limits *in principle*. These occur even though the underlying laws are known and of a deterministic nature.

More generally and again using the example of weather forecasting, this can be formulated as follows:[12] it is possible to know the exact equations of motion for a system, without being able to predict the evolution in time of this system. Although meteorological developments (as it is generally understood) can be completely described by thermodynamic equations, this is of little help. Because all observations are always finitely accurate, the future behaviour cannot be predicted using these equations. Though weather can be predicted in the short run; the chaotic effects described here will still appear in the middle to long run. It is important to see that it is not the system itself that behaves chaotically; its development is, quite the contrary, strictly deterministic. A chaos exists only for us, not for the thing

[11] Cf. H.G. Schuster, *Deterministic Chaos: An Introduction*, Weinheim 1984, p. 2.

[12] This is also the conclusion of a longer argument in: M. Carrier and J. Mittelstrass, *Mind, Brain, Behavior: The Mind-Body Problem and the Philosophy of Psychology*, Berlin and New York 1991, p. 262. Cf. M. Carrier, 'Chaostheorie', in: J. Mittelstrass (ed.), *Enzyklopaedie Philosophie und Wissenschaftstheorie*, vol. 2, 2nd ed., Stuttgart and Weimar 2005, pp. 40-43.

being studied; it results from the imprecision of our knowledge of the initial conditions. But this means that there is an *epistemological limit* that occurs in the phenomenon of deterministic chaos. Although a system is, in fact, strictly deterministic and can be completely understood according to certain laws, we are not in a position to describe the behaviour of this system, despite our precise knowledge of these laws.

Epistemologically speaking the chaos is a *supervenient* characteristic.[13] A characteristic *s* is supervenient to a set of physical characteristics *p*, if (1) *s* is not of a concrete-physical nature, that is, *s* can obtain in physically different systems, and if (2) differences in *s* always coincide with differences in *p* (although not *vice versa*). The occurrence or non-occurrence of chaos always depends on the physical differences in the system.

The second reason is the problem of a *Laplace's demon*. This label (credited to E.H. Du Bois-Reymond)[14] refers to a fictitious superhuman intelligence, which – under the assumption of a stable, closed and all-determined system typical for a mechanistic worldview – knows of all initial conditions of all possible movements and thus can predict the location of any particle for every point in time. Now (as has already been mentioned), quantum mechanical systems – in contrast to relativistic physics, where differential equations describe deterministic systems with regards to their state variables – are non-deterministic with regard to conjugate variables such as position and momentum. Rather, they are statistic, i.e. incalculable even by Laplace's demon – an implication confirmed by recent developments in physics.

There is yet another reason why Laplace's demon is unable to handle the problem of predictability, even under the assumption of deterministic structures.[15] Such a demon would himself be part of the world which he seeks to predict. This situation inhibits *self-reference*: the observing system or measurement device is itself part of the system whose development is being predicted. In other words, predictability in a Laplace's demon situation demands measurability of a system state 'from within'. This, in turn,

[13] Cf. P. Hoyningen-Huene, 'supervenient / Supervenienz', in: J. Mittelstrass (ed.), *Enzyklopaedie Philosophie und Wissenschaftstheorie*, vol. 4, Stuttgart and Weimar 1996, pp. 144-145.

[14] 'Über die Grenzen des Naturerkennens' (1872), in: E. Du Bois-Reymond, *Vortraege über Philosophie und Gesellschaft* (ed. S. Wollgast), Hamburg 1974, pp. 56-57.

[15] For the following see Th. Breuer, *Quantenmechanik: Ein Fall fuer Goedel?*, Heidelberg etc. 1997, pp. 7-21; 'Limits to Self-Observation', in: M. Carrier *et al.* (eds.), *Science at Century's End: Philosophical Questions on the Progress and Limits of Science*, Pittsburgh Pa. 2000, pp. 135-149.

demands, (1) that any object state is connected to the state of an apparatus, hence there can be no object states remaining (though it is possible that apparatus states can exist without a corresponding object state), and (2) that there are no two object states that correspond with the same apparatus state (while conversely there can be two apparatus states which correspond to the same object state).[16] To measure each object state with exactness, it must correspond to at least one apparatus state. This implies first and foremost that there are at least as many apparatus states as there are object states. However, the assumption of the *inner observer* (a demonic situation) implies that there are more object states than apparatus states. An inner observer is indeed part of an object, such that for the inner observer the apparatus states are a proper subset of the object states.

These conditions contradict each other. The demand for exact measurement implies that the apparatus has at least as many states as the object. The condition of the inner observer says that the object has more states than the apparatus. These two conditions cannot hold at the same time. And this is a strong argument for the separation of predictability and determinism. Both arguments, the chaos argument and the argument of the inner observer, make it clear that there can be deep or even basic problems of prediction even in a deterministic framework; hence determinism and unpredictability are not mutually exclusive.

4. Laplace's demon has lost its demonic character in this context; he has become an observing scientist. Thus it has been rightly said: 'In fact, most of the contributors to the debate, having paid lip service to Laplace, almost unnoticeably substitute for his demon a human observer. They thereby reduce determinism to predictability, i.e., the question whether an actual observer, a biologist or a physicist, is able to predict future events. This reduction of Laplacian determinism to actual predictability is a drastic step. On the one hand, it brings the question from philosophical clouds down to earth, where one may hope to find an answer. On the other, it is reduced to a technical question about the state of affairs in the relevant science'.[17] This is also the case with K.R. Popper.

For Popper, who by and large identified determinism and predictability with each other (determinism = predictability with a defined level of exactness, which depends on the degree of knowledge about the initial condi-

[16] In Th. Breuer's presentation this is expressed by the subjectivity of the picture ('Can a picture contain a full and precise picture of itself?'), 'Limits to Self-Observation', p. 135.

[17] N.G. van Kampen, 'Determinism and Predictability', *Synthese* 89 (1991), p. 275.

tions),[18] *scientific determinism* is 'the doctrine that the state of any closed physical system at any given future instant of time can be predicted, even from within the system, with any specified degree of precision, by deducing the prediction from theories, in conjunction with initial conditions whose required degree of precision can always be calculated (in accordance with the principle of accountability) if the prediction task is given'.[19] In this context, Laplace's demon is construed as a disembodied spirit; he is transformed into a 'super-scientist': 'The demon, like a human scientist, must *not* be assumed to be able *to ascertain initial conditions with absolute mathematical precision*; like a human scientist, he will have to be content with a finite degree of precision'.[20] Naturally, this leaves room also for deterministic conceptions.

Popper's critique of determinism in natural science and philosophy employs arguments not only from quantum mechanics, but also from classical physics. He argues that Newtonian mechanics, which is deterministic by conception, is unable to determine initial conditions with the precision necessary for prediction ('principle of accountability'). More generally, according to Popper, the growth of theoretical knowledge is not predictable in principle, which also hints at an *indeterminism* – which could be used, for example, as a solution for mind-body problems.

5. Let me refer in a final part to the concept of *emergence*. Emergence says that it is impossible to use characteristics of elements and the interrelations between these to describe characteristics of ensembles or make predictions about them.[21] Thus a common formula says this: the whole is more than its parts.[22] According to the *emergence thesis*, the world is a levelled structure of hierarchical organised systems, where the characteristics of higher-level systems are by and large fixed by the characteristics of their respective subsystems, yet at the same time essentially different. Different characteristics and processes occur in the respective levels. As well, a weak and a strong emergence thesis can be distinguished from one another.

The core element of the strong emergence thesis is a non-derivability-

[18] Cf. K.R. Popper, 'Indeterminism in Quantum Physics and in Classical Physics', *The British Journal for the Philosophy of Science* 1 (1951), pp. 117-133.

[19] K.R. Popper, *The Open Universe: An Argument for Indeterminism*, Totowa 1982, p. 36.

[20] *Ibid*., p. 34. Cf. J. Earman, *A Primer on Determinism*, pp. 8-10.

[21] For the followings see M. Carrier, 'emergent / Emergenz', in: J. Mittelstrass (ed.), *Enzyklopaedie Philosophie und Wissenschaftstheorie*, vol. 2, 2nd ed., Stuttgart and Weimar 2005, pp. 313-314.

[22] Cf. K. Lorenz, 'Teil und Ganzes', in: J. Mittelstrass (ed.), *Enzyklopaedie Philosophie und Wissenschaftstheorie*, vol. 4, Stuttgart and Weimar 1996, pp. 225-228.

or non-explainability hypothesis of the system characteristics shaped from the characteristics of the system components. An emergent characteristic is non-derivable; its occurrence is in this sense unexpected and unpredictable. Weak emergence is limited to the difference of the characteristics of systems and system components and is compatible with the theoretical explainability of the system characteristics. Weak emergence is essentially a phenomenon of complexity.

The classic rendering of strong emergence is credited to Ch.D. Broad.[23] Broad's motivation was to provide a suitable interpretation of living organism. He intended to depict organisms neither as mere machines nor as being fuelled by an exceptional vital force. This neo-vitalist view was first and foremost endorsed by H. Driesch,[24] who maintained that beings are fitted with 'entelechy', i.e. with purposeful biological powers. Broad was searching for a third way between the mechanistic and the vitalist view on life. The emergence thesis was intended to create this path. Emergent characteristics of ensembles were intended to be roughly defined by the divergent characteristics of their components, yet it was not intended to explain the former on that basis.

Strong emergence is characterised through the following conditions: (1) The condition of *qualitative difference*. This condition applies the emergence thesis to those characteristics of ensembles which differ profoundly from the characteristics of their components. (2) The condition of *characteristic determination*. This condition says that the characteristics of the components are sufficient to let the specific characteristic emerge; emergence is not depended upon further factors. (3) The condition of the *principal gap of explanation*. This condition implies that it is actually impossible to explain the characteristics of ensembles through the characteristics of their components, including their interrelations. – Incidentally, the existence of strong emergent characteristics in this sense is heavily disputed. The only candidates in the running at the moment are currently *phenomenal* characteristics.[25] The point here would be, that in a given neurophysiological arrangement, the occur-

[23] Ch. D. Broad, *The Mind and its Place in Nature*, London 1925.

[24] H. Driesch, *The Science and Philosophy of Organism*, vols. 1-2, London 1908, 2nd ed., London 1929.

[25] See A. Stephan, 'Phaenomenale Eigenschaften, phaenomenale Begriffe und die Grenzen Reduktiver Erklaerung', in: W. Hogrebe and J. Bromand (eds.), *Grenzen und Grenzueberschreitungen* (XIX. Deutscher Kongress fuer Philosophie, Bonn, 23.-27. September 2002). *Vortraege und Kolloquien*, Berlin 2004, pp. 404-416.

rence of qualitative experiences (e.g. blue, the sound of trumpets etc.) in a system would be non-derivable and unpredictable.

Concerning predictability, it is particularly the *temporal* aspect of the emergence thesis which is of interest, i.e. for ensemble characteristics that occur in developments. Limits of reductability (of the whole to its parts) figure here as limits of explanation and predictability. This temporal novelty is described by the concept of *creative advance of nature*. It is endorsed by Popper and Eccles, among others.[26]

6. To sum up: determinism does not imply predictability, and unpredictability does not imply non-determinism. In fact, there is unpredictability in a deterministic world, and unpredictability permits deterministic worlds. This has been illustrated with the discussion of the concepts of deterministic chaos, Laplace's demon, who becomes stripped of all his demonic characteristics, and emergence. Besides, one could not simplify matters by distinguishing (as has been proposed) between ontological determinism and epistemic unpredictability. First, such a distinction is epistemic in itself and second, it merely expresses that the concepts of determinism and predictability do not belong to the same (semantic) level, or even mean the same thing. Predictability, not determinism, is the problem (in some areas). Dealing with unpredictability in the right way is the challenge – in science as well as in ordinary life.

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[26] K.R. Popper and J.C. Eccles, *The Self and Its Brain*, New York etc. 1977, pp. 22-35. Cf. also M. Čapek, *The Philosophical Impact of Contemporary Physics*, Princeton N.J. etc. 1961, pp. 333ff.