# Quantum mechanics: determinism and indeterminism

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**Question**

*Is our world deterministic or indeterministic?*

# Kant’s Third Antinomy

Immanuel Kant, *Critique of Pure Reason*, 1781/7.

In his discussion of the problem of the freedom of the will, Kant offers a thesis and an antithesis:

**Thesis (Thesis)**

*“Causality, according to the laws of nature, is not the only causality from which all the phenomena of the world can be deduced. In order to account for these phenomena it is necessary also to admit another causality, that of freedom.” (A444)*

**Thesis (Antithesis)**

*“There is no freedom, but everything in the world takes place entirely according to the laws of nature.” (A445)*

Let’s look at physics to see whether we can resolve this antinomy...

# Naturalism

**Assumption**

*Let’s start out on a naturalized approach, and hence look to physics for an answer.*

Physics, however, does not render a clear verdict:

1. Against the common presumption, classical Newtonian physics is not straightforwardly deterministic.
2. Whether general relativity is deterministic or indeterministic is a subtle issue.
3. Against the common presumption, quantum physics is not straightforwardly indeterministic.

# Reminder: Defining determinism

Earman, J. (1986), *A Primer on Determinism* (Reidel).

Let $\mathcal{W}$ denote the set of all physically possible worlds, i.e. those possible worlds which are in accordance with the laws of the actual world. Then:

**Definition (Determinism for worlds)**

*A world $w \in \mathcal{W}$ is deterministic if and only if for any $w' \in \mathcal{W}$, if $w$ and $w'$ agree at any time, then they agree for all times. A world that fails to be deterministic is indeterministic.*

**Definition (Determinism for theories)**

*A "theory $T$ is deterministic just in case, given the state description $s(t_1)$ at any time $t_1$, the state description $s(t_2)$ at any other time $t_2$ is deducible [in principle] from $T$." (Earman 1986, 20) A theory that fails to be deterministic is indeterministic.*

# Physical states

**Definition (Physical state)**

*A physical state is the complete description of the (basic) physical properties of the world at a moment in time.*

- Example: in Newtonian physics, a physical state is given by a description of all the locations, motions, and masses of all the bodies in the world, plus the forces acting on them.

# Can we ever *know* the answer?

Suppes, Patrick (1993), 'The transcendental character of determinism', *Midwest Studies in Philosophy* 18: 242-257.

Suppes (1993): question must transcend any possible experience, since

**Theorem (Ornstein)**

*There are "processes which can equally well be analyzed as deterministic systems of classical mechanics or as indeterministic semi-Markov processes, no matter how many observations are made" (254).*

- Suppes assumes that this theorem applies to "most physical processes above a certain complexity level", and so "[f]or a great variety of empirical phenomena there is no clear scientific way of deciding whether the appropriate 'ultimate' theory should be deterministic or indeterministic" (ibid.).

# Can we ever *know* the answer?

Winnie, John A. (1997), 'Deterministic chaos and the nature of chance', in J. Earman and J.D. Norton (eds.), *The Cosmos of Science: Essays of Exploration* (University of Pittsburgh Press), 299-324.

But Suppes's claim does not succeed, as there is an asymmetry between the deterministic and the stochastic description:

- Winnie 1997: While it is typically possible to generate a discrete-time stochastic process from the appropriately partitioned underlying continuous-time deterministic process, the converse is not true: a complete deterministic description of a process contains information on the system's behaviour at scales below the coarse-graining scale, information which a stochastic description lacks.

⇒ Philosophical gloss Suppes puts on Ornstein's theorem incorrect, and so issue may not transcend any possible experience.

# Not as deterministic... Earman's space invaders

Carl Hoefer (2016). Causal determinism. In Edward N. Zalta (ed.), *Stanford Encyclopedia of Philosophy*. https://plato.stanford.edu/archives/spr2016/entries/determinism-causal/.

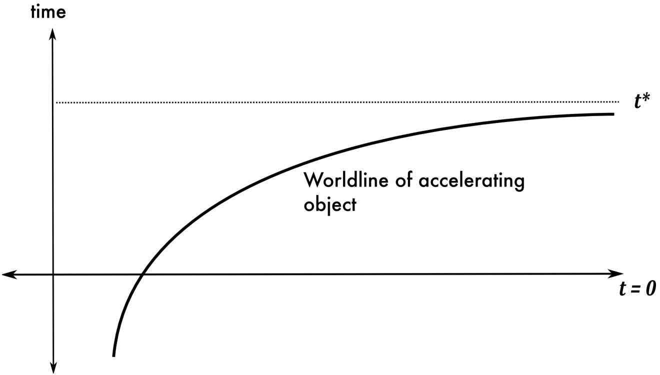


Figure: An object accelerates so as to reach spatial infinity in a finite time

# Violations of determinism: Earman's space invaders

Carl Hoefer (2016). Causal determinism. In Edward N. Zalta (ed.), *Stanford Encyclopedia of Philosophy*. https://plato.stanford.edu/archives/spr2016/entries/determinism-causal/.

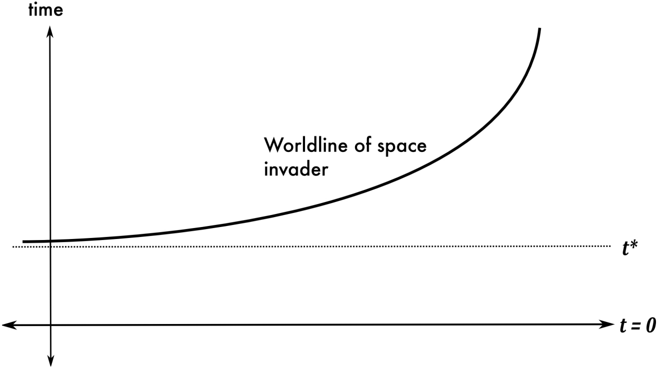


Figure: A 'space invader' comes in from spatial infinity

# Problematic idealizations: collision singularities

- The space invader case results from the fact that in non-relativistic physics, a body can accelerate beyond any bounds. This is fixed once we move to relativity.
- A second type of violations of determinism in classical physics results, arguably, from problematic idealizations.
  - singularities in elastic collisions involving point particles
  - Norton's dome

# Problematic idealizations: Norton's dome

John Norton (2008). The dome: an expectedly simply failure of determinism. *Philosophy of Science* **75**: 786-798. Images from https://www.pitt.edu/~jdnorton/Goodies/Dome/index.html

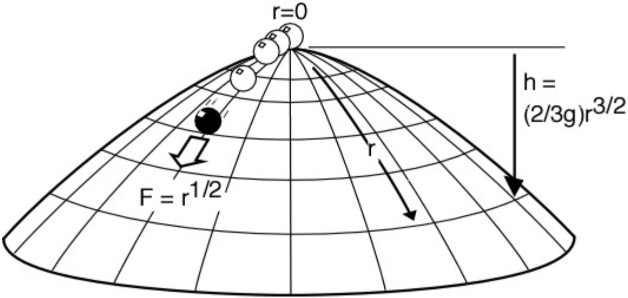


Figure: A unit mass sits at the apex of a radially symmetric, frictionless dome

# Norton's dome: possible motions

The mass which is initially at rest can have the following future motions:

- None: it remains at apex for all times
- Spontaneous acceleration: the mass starts to accelerate in some arbitrary direction at some arbitrary future time

# Indeterminism in general relativity: hole argument

John Norton (2015). The hole argument. In Edward N. Zalta (ed.), *Stanford Encyclopedia of Philosophy*. https://plato.stanford.edu/archives/fall2015/entries/spacetime-holearg/.

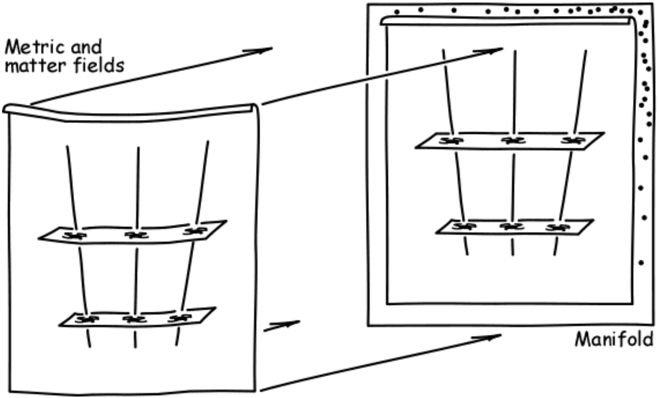


Figure: One way to spread metric and matter over the manifold

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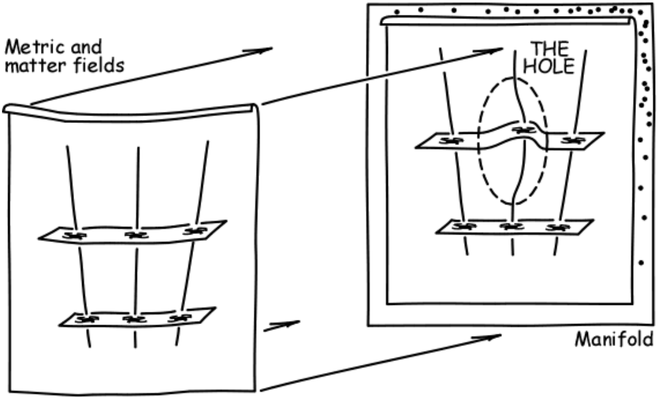


Figure: Another way to spread metric and matter over the manifold

# Quantum mechanics and indeterminism

**Thesis (Formerly orthodox view)**

*QM is an ineliminably indeterministic theory. This indeterminism arises in the measurement process as von Neumann's* Projection Postulate *stipulates a stochastic collapse of quantum state. However, between measurements the dynamical Schrödinger evolution is fully deterministic.*

**Thesis (The Truth)**

*Both parts are false: neither is QM a straightforwardly and ineliminably indeterministic theory, nor is the evolution in the absence of measurements fully and unproblematically deterministic.*

# Schrödinger evolution: almost deterministic

John Norton (1999). *Foundations of Physics* 29: 1265-1302.

John Earman (2009). *Synthese* 169: 27-50.

- The Schrödinger evolution is governed by the Schrödinger equation, which is a first-order, linear differential equation for which existence and uniqueness theorems can be proven. But there are some caveats:
  1. Norton (1999): theorems may fail for Hamiltonian of extreme conditions ("quantum supertasks")
  2. Earman (2009): determinism may fail if Hamiltonian is not essentially self-adjoint
- Overall, for most of the situations that may be considered physically realistic, the Schrödinger evolution is deterministic.

# Measurement problem and determinism

## Characterization (Measurement problem)

*The measurement problem can be stated as the inconsistency of the following three statements that seem to be endorsed or implied by the basic formalism of the theory (Maudlin 1995):*

1. *The wave function $\psi$ completely describes the state of the physical system at stake.*
2. *The linear Schrödinger equation always governs the dynamical evolution of the wave function of the system.*
3. *Measurements of observables of the system have determinate outcomes.*

# Classification of basic types of realist interpretations

## Characterization (Measurement problem)

*The measurement problem can be stated as the inconsistency of the following three statements that seem to be endorsed or implied by the basic formalism of the theory (Maudlin 1995):*

1. *The wave function $\psi$ completely describes the state of the physical system at stake.* $\Rightarrow$ *hidden-variables theories*
2. *The linear Schrödinger equation always governs the dynamical evolution of the wave function of the system.* $\Rightarrow$ *collapse theories*
3. *Measurements of observables of the system have determinate outcomes.* $\Rightarrow$ *many-worlds theories*

# Interpretations and (in)determinism

- Whether QM is a deterministic or an indeterministic theory depends on its interpretation:
  1. hidden-variables theories (e.g. Bohmian mechanics): deterministic or indeterministic
  2. Collapse theories (e.g. GRW): indeterministic
  3. many-worlds theories (e.g. Everett): deterministic (to extent Schrödinger equation is deterministic)

# Bohmian and Nelsonian mechanics

- Bohmian mechanics takes precisely positioned particles, the wave-function (and, if present, force fields) as fundamental.
- The dynamics is given by the Schrödinger equation and the guiding equation, for which existence and uniqueness results can be proven.

$\Rightarrow$ Bohmian mechanics is a deterministic theory.

# Bohmian and Nelsonian mechanics

- Nelsonian mechanics similarly regards elementary particles as fundamental; the status of the wave-function is debated.
- On the (heterodox) acceptance of the wave-function into the fundamental ontology, the dynamics is then given by the (deterministic) Schrödinger equation and a ineliminably stochastic guiding equation.

$\Rightarrow$ Nelsonian mechanics is an indeterministic theory.

# Bohmian and Nelsonian mechanics

- Nelsonian mechanics and Bohmian mechanics are empirically equivalent theories.
- They are similarly simple.
- Bohmian mechanics, as it stands, is explanatorily more powerful though.

# The role of theorems in the debate on HV theories and determinism

- But: all interpretations are constrained by the mathematical formalism of QM...
- There is a long history of alleged results against HV theories: von Neumann’s no-go proof, Gleason’s theorem, Bell’s theorem, Kochen-Specker theorem...
- In a nutshell: they all constrain—but fail to rule out—HV theories (in particular Bohmian mechanics)
- In fact, they constrain any interpretation of QM.

# The 'Free Will Theorem'

Conway, John H. and Kochen, Simon (2009), 'The strong free will theorem', *Notices of the American Mathematical Society* 56: 226-232.

There are a number of results in quantum mechanics that have been heralded as proofs of indeterminism. The latest (and most flagrant) case:

**Theorem (Free will)**

*Under three seemingly innocuous assumptions, Conway and Kochen show that a response of a spin-1 particle in a certain experiment is not 'free', i.e. "is not a function of properties of that part of the universe that is earlier than this response with respect to any given inertial frame." (228)*

**Nota bene**

*Conway and Kochen think that "it is natural to suppose that [the particles'] freedom is the ultimate explanation of our own" (230). And they also think that their result renders "compatibalist" [sic!] approaches to the metaphysics of free will obsolete!*

# The 'Free Will Theorem'

Wüthrich, Christian (2011), 'Can the world be shown to be indeterministic after all?', in C. Beisbart and S. Hartmann (eds.), *Probabilities in Physics*, Oxford: Oxford University Press (2011), 365-389.

Conway and Kochen offer a sweeping interpretation of their result:

> *Although... determinism may formally be shown to be consistent, there is no longer any evidence that supports it, in view of the fact that classical physics has been superseded by quantum mechanics, a non-deterministic theory. The import of the free will theorem is that it is not only current quantum theory, but the world itself that is non-deterministic, so that no future theory can return us to a clockwork universe. (ibid., 230; my emphasis)*

⇒ So not only can we know the answer—we already do...

- Wüthrich 2011: unfortunately, a theorem is only as good as its premises, and this one is indeterminism in, indeterminism out

# Evaluation

The ‘Free Will Theorem”s consequences are far less radical than claimed:

1. While Conway and Kochen’s assertion that granted their three premises, their ‘Free Will Theorem’ shows that nature itself is indeterministic is true, the Bohmian/determinist need not accept the premises.
2. Their claim that the ‘Free Will Theorem’ rules out relativistic collapse theories is demonstrably false.

## Conclusion

*It seems as if we’re back to Kant’s Third Antinomy...*