Radboud Universiteit

Thesis Philosophy of Natural and Life Sciences

Spontaneity in Nature

and its Relation to Randomness and Indeterminism

Silvester Borsboom BSc
Author

Prof. dr. Henk de Regt
Supervisor

Student number:
s1107436

Number of words:
19880

May 30, 2024

The term 'spontaneous' appears in various contexts in modern physics, but it also has a long history in natural philosophy. Its Greek analogue *to automaton* is studied by Aristotle, and the Latin phrase *sponte sua* is used extensively by Lucretius. Peirce also introduces spontaneity in the context of his tychism. In this thesis we give a historical overview of these uses of spontaneity and compare them to spontaneity in thermodynamics and quantum mechanics. We examine the relation to quantum measurement. We argue that in the Copenhagen interpretation, no quantum event can be said to be truly spontaneous, but that true spontaneity does exist in spontaneous collapse theories. Finally we investigate the relation of spontaneity to randomness and indeterminism.

Thesis to obtain the degree of "Master of Arts" in philosophy at
Radboud University Nijmegen

Hereby I, Silvester G.A. Borsboom, declare and assure that I have composed the present thesis with the title *Spontaneity in Nature and its Relation to Randomness and Indeterminism*, independently, that I did not use any other sources or tools other than indicated and that I marked those parts of the text derived from the literal content or meaning of other works – digital media included – by making them known as such by indicating their source(s). Amsterdam, May 30, 2024.

Contents

1 Introduction **4**

2 Historical Background **6**

- 2.1 Aristotle on chance and spontaneity 8
- 2.2 Atoms and their swerve in Lucretius 10
- 2.3 Peirce's tychism 13

3 Spontaneity in Physics **17**

- 3.1 Entropy and spontaneity 18
- 3.2 Spontaneous quantum phenomena 20
  - 3.2.1 Spontaneous emission 21
  - 3.2.2 Spontaneous symmetry breaking 23
- 3.3 Spontaneous collapse theories 25
- 3.4 Back to history 27
  - 3.4.1 Potentiality, actuality and spontaneity 27
  - 3.4.2 The swerve and localisation 28
  - 3.4.3 Peirce and the laws of thermodynamics 30
  - 3.4.4 Tychism in a quantum world 31

4 Spontaneity, Randomness and Indeterminism **34**

- 4.1 Chance and randomness 34
- 4.2 Causal (in)determinism 37
- 4.3 Spontaneity and time 38
  - 4.3.1 Passive spontaneity 39
  - 4.3.2 Active spontaneity 42

5 Conclusion **44**

Chapter 1

Introduction

Quantum mechanics has revolutionised our view of the microscopic world. Whereas before the advent of quantum theory even the smallest physical entities were ascribed specific well-defined quantities, such as position, velocity and energy, physicists have since resorted to a calculus of *probabilities*. In quantum physics, one does not say an electron is precisely there and moves with exactly that speed; instead, one describes it by means of a *wave function*, which allows for the calculation of the probability of finding the electron in a region of space. The picture of the universe thus sketched by quantum theory is one in which *chance* and *randomness* play a fundamental role; one in which *determinism* and *causality* apparently fail; one, even, in which things come about *spontaneously*.

Now, of the concepts italicised in the final sentence of the above paragraph, the last has not received its due attention. This is exemplified by the fact that the *Stanford Encyclopedia of Philosophy* contains entries titled *Chance vs Randomness*[1] and *Causal Determinism*,[2] while no such pages can be found for 'spontaneity'.[3] Various reasons for this lack may be conceived, although it is certain that the notion is not uninteresting, seeing that it was already treated by Aristotle and has played a central role in various philosophical systems, such as those of Leibniz[4] and Kant,[5] and even in Daoism.[6] However, it is not immediately clear whether all these appearances of spontaneity really point to a common concept, or whether it is rather a Wittgensteinian family resemblance, as seems to be the case for randomness.[7] One major aim of this thesis is to show that, if we restrict our attention to spontaneity in *nature*, there is in fact a common meaning, from antiquity to modern philosophy to quantum physics. We wish to show that spontaneity in nature is a concept that both deserves investigation in itself and can also help us deepen our thinking about chance, randomness, determinism, causality and their relation, especially in the context of quantum theory.

---

[1] Antony Eagle, "Chance versus Randomness," in *The Stanford Encyclopedia of Philosophy*, Spring 2021, ed. Edward N. Zalta (Metaphysics Research Lab, Stanford University, 2021), accessed February 3, 2024, https://plato.stanford.edu/archives/spr2021/entries/chance-randomness/.

[2] Carl Hoefer, "Causal Determinism," in *The Stanford Encyclopedia of Philosophy*, Winter 2023, ed. Edward N. Zalta and Uri Nodelman (Metaphysics Research Lab, Stanford University, 2023), accessed February 3, 2024, https://plato.stanford.edu/archives/win2023/entries/determinism-causal/.

[3] Though using the search query 'spontaneity' does yield a variety of related results.

[4] Donald Rutherford, "Leibniz on Spontaneity," in *Leibniz: Nature and Freedom*, ed. Donald Rutherford and J. A. Cover (Oxford University Press, January 4, 2005).

[5] Marco Sgarbi, *Kant on Spontaneity*, Continuum Studies in Philosophy (London ; Continuum, 2012).

[6] Chad Hansen, "Daoism," in *The Stanford Encyclopedia of Philosophy*, Spring 2020, ed. Edward N. Zalta (Metaphysics Research Lab, Stanford University, 2020), accessed March 6, 2024, https://plato.stanford.edu/archives/spr2020/entries/daoism/.

[7] Klaas Landsman, "Randomness? What Randomness?," *Foundations of Physics* 50, no. 2 (February 1, 2020): 61–104.

Our interest in the spontaneity of nature did not arise out of thin air like Lucretius' *simulacra* (see section 2.2). It was aroused by the simple observation that the word 'spontaneous' appears in various places in quantum theory, e.g. in 'spontaneous emission', 'spontaneous symmetry breaking' and 'spontaneous collapse'. In an effort to better understand the meaning of spontaneity in these quantum concepts, it was found that the term already has a long history in natural philosophy, starting, as always, in antiquity. In addition, reflection on the role of randomness in supposedly spontaneous quantum phenomena led to the intuition that spontaneity and randomness are somehow inextricably linked by Father Time.

These considerations already contain the three approaches envisioned in our study of spontaneity in nature, viz. the historical, scientific and philosophical. We wish to discover what role spontaneity has already played in natural philosophy, what it means in modern physics, and how it relates to randomness and indeterminism through *time*. We want to find inspiration in history in order to reflect on the physics and the metaphysics, so that we can finally ask: does our universe as we now understand it exhibit pure spontaneity? Our research question, then, may be most succinctly formulated as follows.

> **RQ:** What is spontaneity in natural philosophy and physics and how does it relate to randomness and indeterminism?

To answer this question we commence with a historical overview preceded by some etymology in chapter 2. We take Aristotle as our starting point in antiquity, but we spend time especially on Lucretius, an Epicurean whose usage of spontaneity in describing the behaviour of atoms and their *swerve* is highly relevant for us. The Epicureans in turn greatly influenced Charles Sanders Peirce,[8] the founder of American pragmatism.[9] Peirce developed a view of the cosmos exhibiting a ubiquitous spontaneity in the guise of continuous deviation from natural law. We also briefly mention other less directly relevant thinkers, such as Leibniz and Kant.

Subsequently, we work out our scientific approach to spontaneity in chapter 3 by considering its appearance in thermodynamics and quantum theory, relating this to the conceptions of spontaneity presented in chapter 2. We study spontaneous emission and spontaneous symmetry breaking and examine the role of quantum measurement in relation to spontaneity. In doing so the need arises to investigate interpretations of quantum theory other than the standard Copenhagen interpretation, most notably the so-called *spontaneous collapse theories*. We ask ourselves in what sense quantum phenomena can be said to be spontaneous and how the answer to this question depends on our interpretation of quantum theory.

In chapter 4 we move on to doing proper metaphysics by reflecting on the way spontaneity relates to randomness and indeterminism. We argue for two theses about spontaneity and its relation to time, leading us to a discussion of the status of spontaneity in our universe. We then summarise our results and present our conclusions in chapter 5.

---

[8] Max H. Fisch, "Peirce's Arisbe: The Greek Influence in His Later Philosophy," *Transactions of the Charles S. Peirce Society* 7, no. 4 (1971): 187–210.

[9] Robert Burch and Kelly A. Parker, "Charles Sanders Peirce," in *The Stanford Encyclopedia of Philosophy*, Spring 2024, ed. Edward N. Zalta and Uri Nodelman (Metaphysics Research Lab, Stanford University, 2024), accessed January 21, 2024, https://plato.stanford.edu/archives/spr2024/entries/peirce/.

Chapter 2

Historical Background

Since the term ‘spontaneous’ is the central interest of this thesis, it is high time we consider its etymology. It derives from the Latin phrase *sponte sua*, which consists of the feminine noun *spons* “will, volition” and the possessive pronoun *suus*, both in the ablative case.[1] The ablative or fifth case is used to denote source, origin or instrument, so *sponte sua* can be translated as “of one’s own accord” or “willingly”. Current usage of ‘spontaneous’, however, does not necessarily refer to any volition. We might say, for instance, that something “explodes spontaneously,” without implying that the entity in question really has “willed” its own explosion. A contemporary definition of spontaneous is: “performed or occurring as a result of a sudden impulse or inclination and without premeditation or external stimulus.”[2] Possible synonyms are: ‘automatic’, ‘unforced’ and ‘unprompted’. In this thesis we will see that “without external stimulus” is a very apt characterisation of spontaneity in nature in the most general sense.

Knowing that the term ‘spontaneous’ originated from *sponte sua*, a logical next step is to see if this phrase is used literally in any Latin natural philosophy. This is indeed the case: the Roman poet Lucretius uses it frequently in his famous *De Rerum Natura*, a beautiful didactic poem expressing his Epicurean worldviews. Lucretius, then, could be a logical beginning for our historical investigation of spontaneity in nature. However, ‘spontaneity’ has a Greek predecessor: *to automaton*, which is composed of *autos* “self” and *matos* “thinking, animated” and is used in the sense of “self-moving”, “self-acting”.[3] It appears already in the works of Democritus and Plato, but Aristotle is the first to systematically study it,[4] most notably in relation to chance in book 2 of the *Physics*, which we shall therefore take as our starting point.

After examining Aristotle and Lucretius in sections 2.1 and 2.2, we jump ahead nearly two millenia to Charles Sanders Peirce in section 2.3. We do so because there is a very interesting direct influence of the Epicurean ideas about spontaneity on Peirce, which we wish to highlight. We also study Peirce’s thought for it’s own sake, since it contains highly relevant ideas, and his admission of “pure spontaneity” sometimes seems like a prophetic anticipation of quantum theory.

Of course, spontaneity appears not only in the works of Aristotle, Lucretius and Peirce throughout

---

[1] “Online Etymology Dictionary,” accessed January 19, 2023, https://www.etymonline.com.

[2] “Oxford Languages and Google - English | Oxford Languages,” accessed February 4, 2024, https://languages.oup.com/google-dictionary-en/.

[3] “Online Etymology Dictionary.”

[4] Joachim Friedrich Ritter et al., *Historisches Wörterbuch der Philosophie*, Völlig neubearb. Ausg., vol. Se-Sp (Darmstadt: Wissenschaftliche Buchgesellschaft ; 1971), p. 1424.

the history of philosophy. In fact, the notion has played an important role in various contexts, of which the *Historisches Wörterbuch der Philosophie* distinguishes three main uses:[5]

- representing phenomena of self-activity in nature;
- characterising, in practical terms, externally unforced actions that occur from inner drive and ability;
- designating, in epistemology, self-driven acts of understanding, with occasional contact with the concept of self-movement.

Of these, it is only the first that is relevant for our purposes, since we are interested in spontaneity in nature and not in spontaneous actions (the second) or the spontaneity of the mind (the third). This means that we leave aside various famous modern philosophers, but we will now briefly mention them for the sake of completeness. To begin with, Descartes speaks of spontaneity as a type of freedom.[6] Leibniz also uses spontaneity in his account of freedom,[7] but it is actually a much broader notion in his thought. Indeed, he widened the concept's scope and systematisation[8] and largely introduced it into early modern philosophy,[9] though it had been briefly considered by Hobbes[10] and, as we said, by Descartes. This broader spontaneity concerns the idea that "all substances or monads possess perfect spontaneity, that is, that all states of a given monad originate within it."[11] Monads do not interact with each other, but each one produces all of its states by itself, with God establishing the harmony between them. This idea of ubiquitous spontaneity is dubbed the 'spontaneity thesis' by Jorati,[12] and it clearly demonstrates the potential breadth of the concept. However, it is too broad for our purposes: if every monadic action is perfectly spontaneous, then this does not enable us to differentiate and it is difficult to concretely apply this to quantum theory. Hume also discusses spontaneity in distinguishing between "liberty of spontaneity" (an agent acting according to its own will) and "liberty of indifference" (a negation of necessity and causes).[13] Kant, in turn, had been influenced by Leibniz' ideas on spontaneity, transmitted to him by Christian Wolff.[14] He made the major innovation - although he had predecessors[15] - of the spontaneity of the mind as its capacity to synthesise raw, unstructured sensory data. This exemplifies the third of the three uses distinguished above. Kant also considers a different notion: the spontaneity of a chain of causally connected phenomena beginning by itself,[16] and it is related to the *unconditioned*.[17] However, Kant discusses this type of spontaneity in the context of transcendental freedom and not in nature. We

---

5. Ritter et al., p. 1424.
6. Joseph Keim Campbell, "Descartes on Spontaneity, Indifference, and Alternatives," in *New Essays on the Rationalists*, ed. Rocco J. Gennaro and Charles Huenemann (Oxford University Press, February 1, 2003), 179–199.
7. Rutherford, "Leibniz on Spontaneity."
8. Ritter et al., *Historisches Wörterbuch der Philosophie*, p. 1426.
9. Sgarbi, *Kant on Spontaneity*, p. 21.
10. Ritter et al., *Historisches Wörterbuch der Philosophie*, p. 1426.
11. Julia Jorati, "Three Types of Spontaneity and Teleology in Leibniz," *Journal of the History of Philosophy* 53, no. 4 (2015): p. 669.
12. Julia Jorati, *Leibniz on Causation and Agency* (Cambridge: Cambridge University Press, 2017).
13. Paul Russell, "Hume on Free Will," in *The Stanford Encyclopedia of Philosophy*, Fall 2021, ed. Edward N. Zalta (Metaphysics Research Lab, Stanford University, 2021), accessed February 26, 2024, https://plato.stanford.edu/archives/fall2021/entries/hume-freewill/.
14. Sgarbi, *Kant on Spontaneity*, p. 23.
15. Corey W. Dyck, "Spontaneity before the Critical Turn: The Spontaneity of the Mind in Crusius, the Pre-Critical Kant, and Tetens," *Journal of the History of Philosophy* 54, no. 4 (2016): 625–648.
16. Ritter et al., *Historisches Wörterbuch der Philosophie*, p. 1429.
17. Sgarbi, *Kant on Spontaneity*.

will therefore not use his ideas any further either. Neither do we consider the German idealists who sought to "bridge the realms of necessity and spontaneity,"[18] nor the phenomenologists and the existentialists.

All in all, we see that only a small part of the philosphical work on spontaneity is directly relevant for us since we are concerned solely with spontaneity in nature. To this end we have found Lucretius and Peirce to be especially inspiring sources. But we cannot forget Aristotle, whose work shaped Western intellectual life for about two millenia, so let us begin there!

2.1 Aristotle on chance and spontaneity

In chapters four to six of book II of the *Physics*, Aristotle considers whether chance and spontaneity (*hê tuchê kai to automaton*) should figure among the various causes that he has treated earlier in the work. He wishes to inquire "whether they are the same or different, and generally what chance and spontaneity are"[19] (*Physics* 195b35-36). As usual, he begins with a historical overview of these concepts. Surprisingly, although earlier philosophers have admitted chance and spontaneity in their cosmologies, they have failed to give a proper account of them.[20] This, then, is the task that Aristotle takes upon himself.

Aristotle mentions Empedocles, who "says that the air is not always separated into the highest region, but as it may chance"[21] (*Physics* 196a21-22). He then discusses those "who actually ascribe this heavenly sphere and all the worlds to spontaneity"[22] (*Physics* 196a25-26), in which he is thinking especially of the atomist Democritus,[23] a contemporary of Socrates. Democritus, in Aristotle's words, maintains that "the heavenly sphere and the divinest of visible things arose spontaneously, having no such cause as is assigned to animals and plants"[24] (*Physics* 196a32-33). According to Aristotle, this idea is absurd and gets it exactly wrong. After all, it is clearly the heavens that exhibit a faultless order which is exempt from any chance variations or spontaneity, whereas the sublunary domain is full of randomness and irregularities.

Accordingly, Aristotle distinguishes between two classes of (mostly) regular things "that always come to pass in the same way" or "for the most part"[25] (*Physics* 196b10-11), and a third class events which are irregular and do not usually happen in the same way. Moreover, in accordance with his teleological worldview, he makes another, independent division: some things "come to be for the sake of something, others not"[26] (*Physics 196b17-18*). The things which both belong to the third, irregular class, but are also in *accidental* connection to the phrase "for the sake of something," are

---

[18] Andrew Bowie, "Friedrich Wilhelm Joseph von Schelling," in *The Stanford Encyclopedia of Philosophy*, Spring 2023, ed. Edward N. Zalta and Uri Nodelman (Metaphysics Research Lab, Stanford University, 2023), accessed February 26, 2024, https://plato.stanford.edu/archives/spr2023/entries/schelling/.

[19] Aristotle, Barnes, and Jonathan, "Complete Works of Aristotle, Volume 1 : The Revised Oxford Translation," in *Complete Works of Aristotle, Volume 1 : The Revised Oxford Translation*, 6. print., with. corr., Bollingen Series (General) ; 192 (Princeton, NJ: Princeton University Press, 2014), p. 334.

[20] Christoph H. Lüthy and Carla Rita Palmerino, "Conceptual and Historical Reflections on Chance (and Related Concepts)," in *The Challenge of Chance: A Multidisciplinary Approach from Science and the Humanities*, ed. Klaas Landsman and Ellen van Wolde, The Frontiers Collection (Cham: Springer International Publishing, 2016), p. 19.

[21] Aristotle, Barnes, and Jonathan, "Complete Works of Aristotle, Volume 1 : The Revised Oxford Translation," p. 335.

[22] Aristotle, Barnes, and Jonathan, p. 335.

[23] Lüthy and Palmerino, "Conceptual and Historical Reflections on Chance (and Related Concepts)," p. 19.

[24] Aristotle, Barnes, and Jonathan, "Complete Works of Aristotle, Volume 1 : The Revised Oxford Translation," p. 335.

[25] Aristotle, Barnes, and Jonathan, p. 335.

[26] Aristotle, Barnes, and Jonathan, p. 335.

the ones that are identified as spontaneous or by chance (*Physics* 196b19-31).

This is a rather complex definition of chance and spontaneity, but fortunately Aristotle immediately provides an example (*Physics* 196b33-197a5). He imagines a man in the business of collecting subscriptions for a feast, who goes to some place for an entirely different reason, and accidentally ends up getting his money there. Clearly the man would not normally or regularly go to that place for collecting payments, so the event belongs to the third class of irregular things, but nonetheless it is connected to the phrase "for the sake of something," since the man did end up getting the money he needed to collect. Still, getting the money was not the purpose of the man's visit, so the event was only accidentally connected to this goal.

Now, so far we have only seen Aristotle use chance and spontaneity together, but chapter 6 of the *Physics* is devoted to distinguishing the two: "they differ in that spontaneity is the wider. Every result of chance is from what is spontaneous, but not everything that is from what is spontaneous is from chance"[27] (*Physics* 197a36-37). Chance events are those in which the relevant final causes are conscious purposes of agents capable of choice,[28] i.e. adult humans. Spontaneity, however, does not need this rational agency and can apply to children, non-human animals and inanimate objects such as stones falling on people's heads (*Physics* 197b29-32). Aristotle summarises the idea as follows:

> Hence it is clear that events which belong to the general class of things that may come to pass for the sake of something, when they come to pass not for the sake of what actually results, and have an external cause, may be described by the phrase 'from spontaneity'. These spontaneous events are said to be from chance if they have the further characteristics of being the objects of choice and happening to agents capable of choice.[29] (*Physics* 197b18-23)

What is surprising and counter-intuitive in this passage is Aristotle's statement that spontaneous events may have external causes. This stands in opposition to the definition from the preamble to this chapter of spontaneity as an occurrence *without external stimulus*, and shows that the Aristotelian conception of spontaneity is substantially different from our contemporary idea.

The spontaneous can, however, also be due to internal causes, as seems to be the case for Aristotle's spontaneous generation (*automatos genesis*) of life,[30] which is presented in the *Generation of Animals*.[31] In this phenomenon, life spontaneously comes into existence from inorganic matter. But, at first sight, spontaneous generation does not quite seem to fit the definition of spontaneity from book II of the *Physics*. After all, the coming-to-be of life can seem like a very regular process, and animals are usually very well-adapted to their environments, apparently exhbiting a non-accidental causation.[32] However, the two notions of spontaneity can, at least to some extent, be reconciled.[33] We will not go into further detail on this discussion, since it is only marginally relevant to our purposes

---

[27] Aristotle, Barnes, and Jonathan, p. 337.

[28] Willard M. Miller, "Aristotle on Necessity, Chance, and Spontaneity," *New Scholasticism* 47, no. 2 (1973): p. 209.

[29] Aristotle, Barnes, and Jonathan, "Complete Works of Aristotle, Volume 1 : The Revised Oxford Translation," p. 337.

[30] Miller, "Aristotle on Necessity, Chance, and Spontaneity."

[31] Christos Panayides, "Aristotle on Chance and Spontaneous Generation. A Discussion Note," *Filozofia (Philosophy)* 68, no. 2 (2013).

[32] Panayides.

[33] Emily Kress, "Aristotle on Spontaneous Generation, Spontaneity, and Natural Processes," in *Oxford Studies in Ancient Philosophy, Volume 58*, ed. Victor Caston (Oxford University Press, November 17, 2020); Panayides, "Aristotle on Chance and Spontaneous Generation. A Discussion Note."

and spontaneous generation of life is a superseded scientific theory. We do emphasise that it was generally accepted for a very long time, from antiquity through the middle ages and well into the nineteenth century, with the famous 1859 swan neck flask experiment by Louis Pasteur usually being taken to be the decisive blow to the theory.[34] It is noteworthy that at least some form of spontaneity in nature, be it in biology rather than in physics, was admitted for over two millenia.

2.2 Atoms and their swerve in Lucretius

Spontaneous generation of life is also present in *De Rerum Natura*. Indeed, since Lucretius' account of the origins of life is "marked throughout by the conspicuous absence of gods or teleology",[35] life must arise from the earth, as we see in book V:

> It remains, therefore, that the earth deserves the name of mother which she possesses, since from the earth all things have been produced. And even now many living creatures arise from the earth, formed by the rain and the warm heat of the sun.[36] (5.795-798)

Yet, Lucretius does not actually use the phrase *sponte sua* here, but this term does occur in twenty other passages throughout the work.[37] The first time is in book I:

> Lastly, since we see that cultivated land is better than uncultivated, and returns better fruit by the labour of our hands, it is plain to see that there are first-beginnings of things in the ground which we bring to birth by turning over the fruitful clods with the ploughshare and trenching the soil. But if there were none such, you would see all things without labour of ours, of their own will [*sponte sua*], grow much better.[38] (1.205-211)

Here, then, the spontaneity of things growing refers to their not being laboured on by human hands - there is no external stimulus causing their growth; they are not subject to human activity, but grow of their own. More relevant for us, however, are the appearances of *sponte sua* in book II, which is about atomic motion and the emergent properties of compounds.[39] Especially 2.1059 and 2.1092 are interesting, for they tell respectively of the spontaneous collisions of atoms and of the spontaneity of nature in relation to the gods. But even before these passages, Lucretius presents the famous and notorious atomic *swerve* or *clinamen*, which has to be taken into consideration when studying spontaneity. Indeed, although Lucretius does not use *sponte sua* in his description of the *clinamen*, it is usually interpreted as an instance of spontaneity, as can be seen from the fact that Piet Schrijvers[40] uses the heading "spontane afbuiging" ("spontaneous deflection") for the passage on the swerve in his Dutch translation of *De Rerum Natura*.[41] This passage is as follows:

---

[34] Pasteur Brewing, "Louis Pasteur and the History of Spontaneous Generation," Pasteur Brewing, October 1, 2011, 11:17 p.m. (Z), accessed February 21, 2024, https://www.pasteurbrewing.com/louis-pasteur-and-the-history-of-spontaneous-generation/.

[35] Simon Trépanier, "Lucretius," in *The Stanford Encyclopedia of Philosophy*, Winter 2023, ed. Edward N. Zalta and Uri Nodelman (Metaphysics Research Lab, Stanford University, 2023), accessed January 20, 2024, https://plato.stanford.edu/archives/win2023/entries/lucretius/.

[36] Titus Lucretius Carus, W. H. D. Rouse, and Martin Ferguson Smith, *On the Nature of Things*, New edition, 1 online resource vols. (Cambridge, MA: Harvard University Press Cambridge, MA, 1924), p. 441.

[37] Monte Ransome Johnson, "Nature, Spontaneity, and Voluntary Action in Lucretius," in *Lucretius: Poetry, Philosophy, Science*, ed. Daryn Lehoux, A. D. Morrison, and Alison Sharrock (Oxford University Press, May 16, 2013), 98–130.

[38] Lucretius Carus, Rouse, and Smith, *On the Nature of Things*, p.19-21.

[39] Trépanier, "Lucretius."

[40] A renowned Dutch professor in Latin language and literature at Leiden University.

[41] Lucretius, *De Natuur van de Dingen*, trans. Piet Schrijvers (Groningen: Historische Uitgeverij, 2008), p. 125.

> One further point in this matter I desire you to understand: that while the first bodies are being carried downwards by their own weight in a straight line through the void, at times quite uncertain and uncertain places, they swerve a little from their course, just so much as you might call a change of motion.[42] (2.216-220)

The fact that the swerve is said to occur at uncertain times and places makes it a random event.[43] Thus, the *clinamen* seems to be an instance of spontaneity in the sense of randomness: the atoms swerve by themselves, of their own accord, and absolutely unpredictably. On the other hand, Johnson has argued that spontaneity in Lucretius and the swerve in particular should be understood not as "lack of order or violation of law, but rather lack of external constraint or control and domination."[44] It is beyond our scope to delve into the debate on how to interpret the swerve, but it is important to mention why Lucretius introduces it in the first place: to guarantee the possibility of human freedom by breaking the chain of necessary, deterministic causation. This theme of spontaneity versus causal determinism appears also in Peirce and throughout the rest of this thesis, but we see that the seeds of these ideas are already present in Lucretius! Have we not innovated at all since antiquity?

Keeping in mind the swerve, let us consider the following crucial passage:

> especially since this world was made by nature, and the seeds of things themselves of their own accord [*ipsa sponte sua*], knocking together by chance, clashed in all sorts of ways, heedless, without aim, without intention, until at length those combined which, suddenly thrown together, could become in each case the beginnings of mighty things, of earth and sea and sky and the generation of living creatures.[45] (2.1058-1063)

Here the collisions of atoms (seeds) are described as spontaneous, chance processes leading, without intention, to the formation of all things. The point is above all to exclude any teleology: the atoms do not collide "for the sake of something," as Aristotle would say, but rather without aim. Thus, the spontaneity presented here is a very different one from that discussed by Aristotle, who required a connection to some final cause. Instead, Lucretius' spontaneity is pointless.

It is not immediately clear whether the spontaneity documented in this passage should be understood as a form of randomness, like the swerve. After all, if Lucretius only means to exclude teleology, the atomic collisions could still be causal, deterministic and lawful, as Johnson argues.[46] On the other hand, Lucretius has already introduced the *clinamen*, which we must assume still plays a role in the collisions decribed here. In addition, if the atoms were absolutely subjected to the laws of nature, then in what sense can they be said to behave of their own accord, rather than merely being governed by nature? This question, inspired by Lucretius, will be the central issue in chapter 4. It also comes to the fore only a couple of lines further, where we encounter a different conception of the spontaneous:

> If you hold fast to these convictions, nature is seen to be free at once and rid of proud masters, herself doing all by herself of her own accord [*ipsa sua per se sponte*], without the help of the gods.[47]

---

[42] Lucretius Carus, Rouse, and Smith, *On the Nature of Things*, p. 113.
[43] Trépanier, "Lucretius."
[44] Johnson, "Nature, Spontaneity, and Voluntary Action in Lucretius," p. 101.
[45] Lucretius Carus, Rouse, and Smith, *On the Nature of Things*, p. 177.
[46] Johnson, "Nature, Spontaneity, and Voluntary Action in Lucretius."
[47] Lucretius Carus, Rouse, and Smith, *On the Nature of Things*, p. 181.

The focus here has shifted from the individual atoms to the whole of nature, and *sua sponte* indicates the independence of nature from divine jurisdiction. It is a political term, an antonym to oppression, domination and servitude, which is applied to nature: nature is free from the oppression and domination of the gods. This is part of a broader pattern of political terminology being used in Lucretius' philosophy of nature, another example being "law (*lex*) of nature".[48]

Thus, we seem to have arrived at two opposing types of spontaneity in nature in book II: the spontaneity of atoms moving and swerving of their own accord, and the spontaneity of all of nature as freedom from divine jurisdiction. However, these do not contradict one another, as is shown in Lucretius' transition from nature to the soul in book III:

> And since I have shown of what kind are the beginnings of all things, and in how varying and different shapes they fly of their own accord [*sponte sua*] driven in everlasting motion, and how all things can be produced from these, following next upon this the nature of mind and spirit must now clearly be explained.[49] (3.31-35)

We see here that the primary elements fly in a spontaneous manner, yet are *driven* by incessant motion.[50] It seems, then, that the laws of nature govern the atoms, while there is simultaneously an element of spontaneity in the behaviour of individual particles. Again, this tension between law and spontaneity is the core issue of chapter 4, and also of Peirce's tychism. Before we turn to Peirce, however, we shall briefly examine relevant uses of spontaneity in books IV and V.[51]

In book IV Lucretius explains the activities of the soul by invoking *simulacra*, which are thin atomic films that can be imprints of objects and are constantly emitted in all directions.[52] The senses work through the impact of streams of simulacra, which can in fact also be created spontaneously:

> But that you may not think these images which pass off from things to be the only ones that move about, there are others which arise of themselves [*sponte sua*] and are formed by themselves in this part of the sky called the air.[53] (4.129-132)

Thus the *simulacra* can be spontaneously formed in the air. This is interesting, as it looks like a case of spontaneous creation or even *creatio ex nihilo*, which would be different from the spontaneity of atoms, which consists only of a deflection of motion. On the other hand, the *simulacra* are themselves made up of atoms, and we should probably take their spontaneous formation to mean a chance coming together of many particles.

Lastly, in the opening of book V, Lucretius tells us that we must definitely *not* think that the behaviour of celestial bodies is spontaneous:

> I will explain by what force pilot nature steers the courses of the sun and the goings of the moon; lest by any chance we think that these between heaven and earth traverse their yearly courses free, of their own will [*sponte sua*], and obliging for the increase of crops and of animals, or deem them to revolve by some plan of the gods.[54] (5.76-81)

---

[48] Johnson, "Nature, Spontaneity, and Voluntary Action in Lucretius," p. 101.

[49] Lucretius Carus, Rouse, and Smith, *On the Nature of Things*, p. 191.

[50] Johnson, "Nature, Spontaneity, and Voluntary Action in Lucretius."

[51] There is one mention of *sponte sua* at 6.1021 in the account of magnetism in book VI, but it is not so relevant for us.

[52] Trépanier, "Lucretius."

[53] Lucretius Carus, Rouse, and Smith, *On the Nature of Things*, p. 287.

[54] Lucretius Carus, Rouse, and Smith, p. 385.

The sun and moon do not exhibit spontaneous behaviour and do not move by the will of the gods, but are guided by nature. Unlike the atoms, they cannot swerve of their own accord, as is seen from the fact that their motion is extremely regular. In this, Lucretius seems to agree with Aristotle, against Democritus. If we allow ourselves to make anachronistic analogies, we might see in this an analogy to quantum theory: the microscopic realm of atoms apparently exhibits spontaneity, whereas the macroscopic realm is evidently one of deterministic, continuous motion.

All in all, we have now seen three main ways in which Lucretius invokes spontaneity to describe nature:

- the spontaneous collisions of atoms, which are (at least partly) due to the *clinamen*, which is itself spontaneous;
- the spontaneity of nature as independence from the gods;
- the spontaneous formation of *simulacra*.

The simulacra will not play a further role in this thesis, but for the sake of completeness they could not be omitted. The spontaneity of nature as a whole, i.e. the second of the above three, is something that we take largely for granted nowadays, and its modern incarnation might be the idea that everything is determined by the laws of nature and not by divine intervention. Lastly, the first, i.e. the spontaneous behaviour of individual particles, is something which one might say is now thought to exist in quantum theory. We will return to this comparison in chapter 3.

2.3 Peirce's tychism

Right before the quantum revolution, the Epicureans inspired Charles Sanders Peirce, who was not only a philosopher but also a mathematician, physicist and logician. For him, spontaneity is a continuous deviation from the laws of nature. His view of the cosmos, in which such spontaneity is ubiquitous, is known as *tychism*, after the Greek word for chance *tuchê* that we met in section 2.1. In developing his tychism, Peirce's encounter with the Epicureans (and among them Lucretius) and in particular the swerve played a decisive role.[55] For Peirce, it was not about the actual existence of the Epicurean atoms: "what mattered was that here at last was a physical model of an absolute chance, beside which the chance of the calculus of probabilities, of the statistical theory of gases, or of Darwin's fortuitous variations, was but quasi-chance."[56] It is not surprising therefore that Peirce begins *The Doctrine of Necessity Examined* by recalling the ancient atomists: "Epicurus [...] found himself obliged to suppose that atoms swerve from their courses by spontaneous chance; and thereby he conferred upon the theory life and entelechy."[57] It is interesting that Peirce goes so far as to state that the swerve gives *life*, and we will shortly understand why he believes this. Moreover, we note that Peirce calls the swerve *spontaneous chance*, along the lines of our discussion of the *clinamen* in section 2.2 above.

To understand Peirce's idea of spontaneity we must first go back to his motivation for renouncing the "doctrine of necessity". This doctrine refers to the causal determinism that finds its ultimate

---

[55] Fisch, "Peirce's Arisbe," p. 190.
[56] Fisch, p. 192.
[57] C. S. Peirce, "The Doctrine of Necessity Examined," *The Monist* 2, no. 3 (1892): p. 321.

expression in Laplace's demon (see section 4.2 for more details). Peirce, however, wishes to safeguard the growth, complexity, diversity and freedom that he sees in the cosmos. He does not believe that the full specification of the state of the universe was made *in principio*, in some instant of creation, but rather that this specification occurs continuously and is still happening.[58] Peirce saw this in astronomy, geology, paleontology and biology and thought that the increase in complexity seen in those fields cannot be explained from mere mechanical laws.

This leads us to his central statement about spontaneity in nature:

> by thus admitting pure spontaneity or life as a character of the universe, acting always and everywhere though restrained within narrow bounds by law, producing infinitesimal departures from law continually, and great ones with infinite infrequency, I account for all the variety and diversity of the universe.[59]

We see that spontaneity for Peirce has a random character and is not lawful. In fact, spontaneity is precisely the small, random deviation from the laws of nature. Of course, this reminds us of Lucretius' *clinamen*, and indeed, according to Hobbs:

> Peirce frames this discussion of tychism by way of the ancient debate about whether the fundamental material parts of the world, namely atoms, move about in some determined direction or, on the other hand, whether they somehow swerve spontaneously and unpredictably, thus entering the spontaneity just mentioned. We see that tychism is exemplified by the Epicurean swerve.[60]

But for Peirce, spontaneity is about more than indeterminism - he speaks of "pure spontaneity or life." This reminds us of the *élan vital* by Bergson, in whose work spontaneity also appeared,[61] and possibly of vitalistic theories of the organic, in which the notion of spontaneity played a role too.[62] Yet, Peirce is speaking of the whole universe and its laws, so why does he equate pure spontaneity with life? To understand this we must consider *evolution*, for Peirce was influenced by various sorts of evolutionary thinking: not just by Darwinian evolution in biology, but also by Lyell's evolution of geological structures and Hegel's evolution of ideas, famously developed in the *Phänomenologie des Geistes*. "For Peirce, the entire universe and everything in it is an evolutionary product."[63] Even the laws of nature have evolved: "just as ideas, geological formations, and biological species have evolved, natural habit has evolved."[64] Nature itself exhibits evolution and used to be much more spontaneous than it now is. It has, in a sense, settled into its current laws, which have gradually become more and more rigid.

However, in this *evolutionism*, struggle, strife and greed are not the fundamental engine. Peirce instead speaks of "evolutionary love" and "agapeism", coming from the Greek word *agape*, meaning "love".[65] He wanted to act against social Darwinism, but "the doctrine also had for Peirce a cosmic

---

[58] Peirce, "The Doctrine of Necessity Examined," p. 333.

[59] Peirce, p. 334.

[60] Charlie Hobbs, "Peirce's Tychism and the Epicurean Swerve," *Southwest Philosophical Studies* 30 (2008): p. 3, https://www.academia.edu/598694/Peirces_Tychism_and_the_Epicurean_Swerve.

[61] Ritter et al., *Historisches Wörterbuch der Philosophie*, p. 1432.

[62] Ritter et al., p. 1432.

[63] Burch and Parker, "Charles Sanders Peirce."

[64] Burch and Parker.

[65] Burch and Parker.

significance, which Peirce associated with the doctrine of the Gospel of John and with the mystical ideas of Swedenborg and Henry James."[66] In that evolutionary love we see something of the will that lies at the etymological origin of 'spontaneous': a will to progress and develop in the universe, expressed by means of random spontaneity. This goes further than spontaneity in Lucretius, where the swerve was introduced to make free choice possible, but where the spontaneous behaviour of atoms was completely in vain and without a purpose. In some sense, then, Peirce combines aspects of Aristotle and Lucretius: for him spontaneity is a deviation from natural law, but there is a teleological aspect to it. In the remainder of this thesis the "deviation from natural law" will generally be how we think about spontaneity, and we return to the issue of teleology in section 4.3.

But what precisely does "deviation from natural law" mean? There are two ways we could think about this, and it is important to distinguish them and understand which is meant by Peirce. In fact, the dichotomy we are about to discuss will play a central role in dissecting the meaning of spontaneity throughout this thesis, and leads to our two theses on spontaneity in section 4.3. Following Reynolds, we call the two interpretations of "deviation from law" the *active* and the *passive* interpretations. The active interpretation seems the most obvious, yet is not correct when it comes to Peirce. It assumes a given, exact natural law and posits spontaneity as an occasional disruption, suspension or interruption of the ability of this law to determine events.[67] These disruptions are, in the mathematical sense of the word, *discrete*, because they happen individually and discontinuously. The law always remains rigid, but there are discrete events at specific points in time (and space) which do not conform to the law. We are inclined to understand Lucretius' *clinamen* this way, since it occurs "at times quite uncertain and uncertain places," while the regular, lawful, downward movement of the atoms remains in place.

However, as has become clear from our discussion of Peirce's evolutionism, in which the laws of nature themselves are "malleable" and only become more rigid over time, Peirce's conception of spontaneity is a *passive* deviation from natural law: laws are not assumed to be exact, but rather imperfect in their ability to determine the course of events.[68] A deviation from natural law occurs because causes do not exactly determine their effects, but only give a set of possible outcomes distributed about some mean. Peirce especially liked the so-called *normal distribution*, which is the mathematical probability distribution that is frequently used to model a wide variety of natural and social phenomena. Normal distributions are completely characterised by their *mean* and their *standard deviation*. The passive "deviation" from law, then, is rather a deviation from the mean, with the standard deviation indicating the expected size of such a fluctuation.

In fact, normal distributions enjoy a special status in probability theory because of the *central limit theorem*, which basically states that the sample mean of any random variable is itself a random variable whose distribution converges to a normal distribution as the sample size becomes ever greater and greater. Peirce was inspired by the central limit theorem and the *law of large numbers*[69] in his tychism, and we should interpret the idea of a "deviation from natural law" as an inherently

---

[66] Burch and Parker.

[67] Andrew Reynolds, *Peirce's Scientific Metaphysics: The Philosophy of Chance, Law, and Evolution* (Vanderbilt University Press, 2002), p. 147.

[68] Reynolds, p. 147.

[69] The law of large numbers states that if we repeat a probabilistic trial ever more often, the frequency of an outcome approaches the probability of that outcome as specified by the probability distribution. For a fair coin flip, it states that the ratio of heads and tails approaches 50/50.

probabilistic aspect in the laws themselves.[70] In the theorems just mentioned, Peirce saw evidence for his conception of spontaneity as “producing infinitesimal departures from law continually, and great ones with infinite infrequency.”

The active and passive interpretations of deviation from natural law form a logical transition into our study of spontaneity in quantum theory. Indeed, the quantum realm is often popularly portrayed as a world of fuzziness and indeterminacy, in which we only have probability distributions to predict events. This reminds us of the passive interpretation. On the other hand, the randomness in quantum theory is usually taken to exist only in the measurement process, which is an event at a specific time and place and is more analogous to the active interpretation. Thus, let us leave behind history and turn to modern science!

---

[70] Reynolds, *Peirce’s Scientific Metaphysics*, p. 147-148.

Chapter 3

Spontaneity in Physics

Having examined several important historical uses of spontaneity, we now turn to modern physics to investigate what spontaneity means there and to examine what it has in common with the ideas of Aristotle, Lucretius and Peirce. At first sight, there are clear similarities: Peirce's definition of pure spontaneity as "producing infinitesimal departures from law continually, and great ones with infinite infrequency" reminds us very much of quantum behaviour, which is ubiquitous for the very small, but exceedingly rare for the very large. Indeed, it has been remarked that "obviously, Peirce would not have been the least surprised by the results obtained from measurements at the quantum level."[1] Furthermore, Schrijvers states that "the notion of the *clinamen* has received great attention and discussion in the twentieth century when the phycisist Werner Heisenberg in 1927 pointed out a degree of indeterminacy in the behaviour of subatomic particles"[2] (our translation). The famous contemporary physicist Sean Caroll even calls Lucretius "the first quantum cosmologist."[3] As for Aristotle, various articles have been written about applying his thought in the context of quantum theory.[4]

It is not our aim to vindicate these philosophers from the past by showing that they somehow anticipated quantum mechanics (which would be a highly dubitable project). We are instead seeking to better understand the notion of spontaneity in physics by itself and by comparing it to inspiring conceptions of the spontaneous in philosophy. In order to make such a comparison we study spontaneity in the two main places in which it appears in physics: in thermodynamics, treated in section 3.1, where it is intimately linked to the notion of *entropy*, and in quantum theory.

In quantum theory, however, the term 'spontaneous' is used to describe both specific quantum phenomena as well as certain interpretations of quantum mechanics as a whole. We treat these two cases separately in sections 3.2 and 3.3 respectively. In these sections we also consider the problem of quantum measurement more generally in relation to spontaneity. Although we attempt to construct ties to the material from chapter 2 throughout, we dedicate the final section 3.4 of this chapter explicitly to this purpose. This allows us to draw connections between all we have learned in order to transition into the next chapter.

---

[1] Burch and Parker, "Charles Sanders Peirce."

[2] Lucretius, *De Natuur van de Dingen*, p. 108.

[3] "The First Quantum Cosmologist – Sean Carroll," August 21, 2008, accessed April 16, 2024, https://www.preposterousuniverse.com/blog/2008/08/21/the-first-quantum-cosmologist/.

[4] Boris Kožnjak, "Aristotle and Quantum Mechanics: Potentiality and Actuality, Spontaneous Events and Final Causes," *Journal for General Philosophy of Science* 51, no. 3 (September 1, 2020): 459–480; Alfred Driessen, "Aristotle and the Foundation of Quantum Mechanics," *Acta Philosophica* 29, no. II (2020): 395–414.

3.1 Entropy and spontaneity

Thermodynamics is the domain of physics concerned with concepts such as heat, work, pressure, temperature and energy. It originated in the work of Carnot on steam engines, but was developed into a full-fledged theory around the middle of the nineteenth century by Clausius and Thomson (Lord Kelvin).[5] There are four laws of thermodynamics, labelled from zero to three (but we consider only the first three, i.e. zero, one and two). These are macroscopic laws: they describe large systems (such as steam engines) by macroscopic variables. One of the great triumphs of nineteenth century physics was to derive these thermodynamic laws from the probabilistic behaviour of the microscopic constituents composing thermodynamic systems. This field is known as statistical mechanics and it is inextricably connected to the names of Boltzmann, Gibbs and Maxwell. It greatly impressed Peirce, who saw it as a model for his tychism: the laws of thermodynamics are derived from the assumption that molecules move and collide randomly, and Peirce thought of this as a prime example of the emergence of law from chance.[6] In this section we first briefly introduce some basic notions of thermodynamics. We then focus on entropy and the second law, which allows us to define spontaneous processes.

Thermodynamic systems are typically described in terms of a small number of quantities, such as the temperature T, the internal energy U and the entropy S. Microscopically speaking, the temperature corresponds to the average *kinetic* energy of the constituents, the internal energy is the average *total* energy of the constituents and the entropy corresponds to the number of *microstates* a system can occupy in a given macrostate. Entropy is usually thought of as a measure of *disorder* of the system. A highly ordered system - a crystal or a human being for instance - has a very low entropy, whereas a system at thermodynamic equilibrium has maximal entropy.

It is with these three quantities that the first three laws (i.e. the zeroth, first and second) of thermodynamics are concerned. In fact, each law introduces one of the quantities. To introduce the zeroth law we need to be a bit more precise about the notion of thermal equilibrium, which can have two meanings. When we consider two systems which are connected by a wall that is permeable to heat, we say these systems are in thermal equilibrium if no net heat is exchanged between them. If we consider just one isolated system, we say it is in thermal equilibrium when its temperature is constant and uniform throughout. The zeroth law is about the first meaning:

> **Zeroth law:** if two systems are in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.[7]

The zeroth law leads to the introduction of the temperature T as a measure of whether systems are in thermal equilibrium: they are if and only if their temperatures are equal. However, the zeroth law does not tell us what temperature is microscopically speaking. The reason that the zeroth law is called so is that it was formulated only in the 1930's (though always implicitly assumed), when the names of the first and second laws had become too firmly entrenched to change.[8]

---

5. P. W. Atkins (Peter William), *The Laws of Thermodynamics : A Very Short Introduction*, Very Short Introductions (Oxford: Oxford University Press, 2010).
6. Reynolds, *Peirce's Scientific Metaphysics*.
7. Atkins, *The Laws of Thermodynamics : A Very Short Introduction*.
8. Atkins.

Moving on, the first law of thermodynamics is about the concept of energy. In fact, it tells us that energy is conserved:

> **First law:** the internal energy of an isolated system is constant.[9]

Thus, energy can neither be created nor destroyed, but only changed from one form to another.[10]

Whereas the zeroth and first laws are quite readily understood, the second law requires a bit more work (thermodynamic pun intended). It is about entropy - which is not a very easy concept in the first place - and frequently appears in (fatalistic) popular culture (e.g. in Isaac Asimov's short story *The Last Question*). There are various possible formulations, one of them being the *Kelvin statement*:

> No cyclic process is possible in which heat is taken from a hot source and converted completely into work.[11]

Here *work* has the technical meaning of energy transfer to or from an object by means of an application of force along a diplacement of that object. It can be thought of as useful energy. The Kelvin statement thus tells us that "Nature exerts a tax on the conversion of heat into work, some of the energy supplied by the hot source must be paid into the surroundings as heat."[12] Another formulation of the second law is the *Clausius statement*:

> Heat does not pass from a body at low temperature to one at high temperature without an accompanying change elsewhere.[13]

Thus, heat cannot be transferred in the "wrong direction", i.e. from cold to hot, without doing work to bring that transfer about. In a fridge, for instance, warm objects can be cooled only by using up electricity.

Now, it is not too hard to show that Kelvin's and Clausius's statements are equivalent. Yet, none of them makes reference to the notion of entropy. To understand the role of entropy, we may ask: *why* is it that we cannot perfectly convert heat into work? Why must some energy be lost to the surroundings? Why does heat not flow from cold to hot bodies, even though energy is conserved (i.e. the first law is respected)? These questions point to the existence of another fundamental property of thermodynamic systems which forbids many processes that are permitted by the first law, i.e. that conserve energy. Unlike energy, this other property cannot be a conserved quantity but must always increase, since it gives rise to an inherent asymmetry in thermodynamic processes - it specifies a "wrong" and a "right" direction. Thus, the most famous formulation of the second law refers to this new property:

> **Second law:** the entropy of the universe does not decrease in the course of any spontaneous change.[14]

---

[9] Atkins, p. 22.

[10] One of the deepest results in mathematical physics, *Noether's theorem*, explains that conservation laws are related to symmetries. Through Noether's theorem, conservation of energy corresponds to time translation symmetry. More precisely: the energy of a system is conserved if and only if the laws of that system are invariant under shifts in time. The question of how Noether's notion of energy relates to that of the first law is deep and difficult.

[11] Atkins, *The Laws of Thermodynamics : A Very Short Introduction*, p. 41.

[12] Atkins, p. 41.

[13] Atkins, p. 42.

[14] Atkins, p. 49.

Now our interest is greatly piqued, for we see the word 'spontaneous' appear! Indeed, there is an intimate connection between the second law and the notion of spontaneity in thermodynamics. The Clausius statement implies that heat does not spontaneously - by itself - flow from cold to hot. Such a process can only be non-spontaneous, i.e. driven by some kind of work.[15] Spontaneous thermodynamic processes, on the contrary, do not need an outside source of energy. For isolated systems spontaneous processes are then characterised purely by an increase in the entropy of that system. For open systems, the second law of thermodynamics tells us that the total entropy of a system and its surroundings can never decrease:

$$\Delta S_{\text{total}} = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}} \geq 0,$$

where ΔS stands for "change in entropy". Thus, an open system can actually spontaneously decrease its entropy, but the entropy of the surroundings must then increase by a larger amount:

$$|\Delta_{\text{surroundings}}| \geq |\Delta_{\text{system}}|.$$

In other words, entropy can spontaneously decrease locally, but this must always lead to a greater increase in entropy in the environment. There is no escaping the second law.

We now arrive at the following idea: processes that are spontaneous in the sense of not being subject to external stimulus in the form of work, are characterised by an increase in entropy, be it of the system itself if it is isolated or of the surroundings if it is not. Since we expect the universe as a whole to be an isolated system by definition, its entropy must increase over time and its evolution is spontaneous in this sense. Only by the action of the gods in the guise of a Maxwellian demon[16] could this spontaneous evolution be undone, but then the universe would no longer be spontaneous in Lucretius' sense of being sovereign with respect to divine jurisdiction!

3.2 Spontaneous quantum phenomena

The definition of a spontaneous process in thermodynamics as one in which entropy increases is formulated in the context of classical physics. Now, the concepts of classical statistical physics can be extended to quantum theory, leading to quantum statistical mechanics. However, this is not what we will be concerned with in this section. Instead, we will study examples of spontaneity in quantum mechanics that are not related to any statistical coarse-graining of a large quantity of constituents. Indeed, spontaneous emission occurs for just one single atom. At first sight, then, the sense of spontaneity presented in this section is very different from the thermodynamic definition. Still, there is always the common underlying idea of a process unfolding *by itself*.

---

[15] Atkins, *The Laws of Thermodynamics : A Very Short Introduction*, p. 42.

[16] Maxwell's demon refers to a thought experiment from 1867 which is supposed to show that the second law can be violated, but which has been fiercely debated ever since. One imagines a box with a gas in it, divided into two compartments with a door between them. A being (the "demon") controls the door and lets through gas particles by quickly closing and shutting it. The demon lets only fast-moving gas molecules pass to the right chamber and only slow-moving molecules into the left chamber. Over time, this act allegedly decreases the total entropy.

3.2.1 Spontaneous emission

The first quantum phenomenon that we study is known as spontaneous emission, a concept that originated in work by Einstein from 1916.[17] In the article *Zur Quantentheorie der Strahlung*,[18] Einstein predicted the existence of so-called 'stimulated emission', and by contrast the version of emission that is not stimulated was dubbed spontaneous.[19] In both spontaneous and stimulated emission an atom lowers its excited energy state by emitting a photon (a light particle). In this process, an electron moves from a higher energy level to a lower one. In Bohr's famous atomic model, emission is visualised by depicting an atom as a nucleus around which orbits an electron, and a higher energy level is then understood as an orbit which is further away from the nucleus. When an electron "teleports" from a higher to a lower orbit, energy is emitted, and it is precisely that amount of energy which is carried away by a photon according to the relation

$$E = h\nu,$$

where E denotes the energy of the photon, h is Planck's constant and ν stands for the frequency of the photon's oscillations.

Now, in the case of stimulated emission there is a clear cause of the process: another incoming photon. Einstein showed that, when an incident photon approaches an excited atom, the atom is likely to emit a new, second photon. This is often visualised as in figure 3.1.[20]

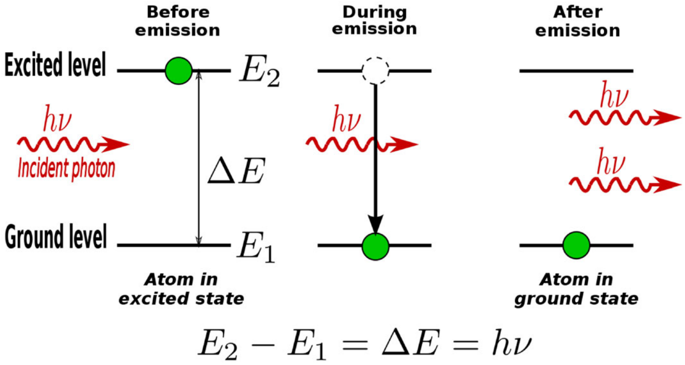

Figure 3.1 Stimulated emission of a photon by an atom. An incident photon interacts with an electron in an excited energy level, thereby causing the emission of a second photon. The electron jumps to a lower energy level in the process.

In the case of spontaneous emission, however, there is no incoming photon at all. Instead, an atom lowers its energy *by itself* by emitting a photon - there is no external stimulus making it do so. In this sense it seems as though the atom does this of its own "will", so *sponte sua*, although in reality we do not ascribe anything like a will to an atom (except, possibly, in theories like panpsychism). We cannot predict the moment at which spontaneous emission occurs: it is random. We can, however, construct a probability distribution that tells us the probability of the atom having decayed (i.e.

---

[17] Norbert Straumann, "Einstein in 1916: "On the Quantum Theory of Radiation"," March 23, 2017, arXiv: 1703.08176.

[18] Martin J. Klein, A.J. Kox, and Robert Schulman, eds., *Collected Papers of Albert Einstein, Vol. 6: The Berlin Years / Writings 1914-1917*, vol. 6, Collected Papers of Albert Einstein (Princeton University Press, 1996), p. 381.

[19] "This Month in Physics History: Einstein Predicts Stimulated Emission," *American Physical Society News* 14, no. 8 (2005).

[20] V1adis1av, *English: A Diagram of Stimulated Emission.*, May 3, 2008, https://commons.wikimedia.org/wiki/File:Stimulated_Emission.svg.

having emitted radiation) after a certain amount of time. This is analogous to radioactivity, where unstable isotopes are characterised by their *half-life*, i.e. the amount of time after which there is a 50% probability of the isotope having decayed.

Let us now ask ourselves: to what extent is spontaneous emission truly spontaneous? In other words: to what extent can an atom really by itself emit a photon? At first sight, our above exposition of the contrast between stimulated and spontaneous emission seems to confirm that spontaneous emission is really spontaneous. After all, there is no external stimulus in the form of an incoming photon. However, the issue is subtler and more profound. After all, we must not forget that *measurement* plays an essential role in understanding the behaviour of quantum systems.

To clarify this point we must turn to the foundations of quantum mechanics in the standard "Copenhagen" interpretation[21] (in section 3.3 we consider an alternative interpretation). In this interpretation, one distinguishes two ways in which a quantum system can evolve: the deterministic, necessary, lawful, *unitary evolution* described by the Schrödinger equation, and the random, indeterministic, lawless, *projective evolution* playing a role only in quantum measurements. In the first type of evolution, the future can be predicted from the present or past and the past can be reconstructed from the present. For the second type, this is not possible.

One difficulty with this twofold picture of quantum evolution is that it is not clear where precisely the demarcation lies, leading to the famous Schrödinger's cat paradox. This difficulty is known as the *measurement problem*, and it is important in our investigation into spontaneity. To understand why, we again consider the excited atom undergoing spontaneous emission. If we do not measure the atom for a while, it exists in a superposition state of having decayed and not having decayed, i.e. a superposition of having and not having emitted a photon. It is only when we measure the atom that we know whether it has decayed or not. Thus, one could argue that an atom never emits a photon spontaneously, by itself, until there is an external stimulus in the guise of measurement.

This conclusion that spontaneous emission is not spontaneous is counter-intuitive, so let us consider a concrete example: how does it work when we are continuously observing a Geiger counter that clicks if it detects radiation emitted by an atom? In that case we wait until suddenly, at a random moment, we hear the Geiger counter click and conclude that the atom has decayed. This emission really seems to be entirely spontaneous: it was not the Geiger counter that forced the atom to decay, right? Nonetheless, a measurement must occur *somewhere*, as stipulated by the very axioms of the Copenhagen interpretation. However, the measurement in question could be induced by something much simpler than the Geiger counter or our own consciousness, like the interaction of the atom with its environment. Still, it remains true that the atom subsists in its superposition state until it is measured in one way or another. By using the Geiger counter we, in a sense, continuously ask the atom whether it has decayed yet. The answer remains "no" right until the moment the atom "decides" to decay and the Geiger counter registers a click. This is some form of spontaneity, for the atom "chooses" of its own accord when to respond: "yes, I am decayed". Still, in this analysis of spontaneous emission in the Copenhagen interpretation we are dealing with a weaker type of spontaneity than pure self-movement, since there *has* to be a measurement somewhere if the decayed state of the atom is to be instantiated. We cannot ignore the interaction between the atom

---

[21] Jan Faye, "Copenhagen Interpretation of Quantum Mechanics," in *The Stanford Encyclopedia of Philosophy*, Summer 2024, ed. Edward N. Zalta and Uri Nodelman (Metaphysics Research Lab, Stanford University, 2024), accessed May 3, 2024, https://plato.stanford.edu/archives/sum2024/entries/qm-copenhagen/.

and the measurement device (whatever consitutes that device), and we can only observe a form of quantum spontaneity in which measurement as an external stimulus is present.

3.2.2 Spontaneous symmetry breaking

Similar considerations play a role when assessing the status of spontaneity in spontaneous symmetry breaking (SSB), a widespread concept in physics that has recently received attention from philosophers.[22] Spontaneous symmetry breaking is invoked as an explanation for various phenomena, such as ferromagnetism, superconductivity and the Higgs mechanism. It is, however, not exclusively a quantum phenomenon, for it exists also in classical mechanics.[23] We first treat the classical case by way of introduction and then continue to the quantum version.

To explain what spontaneous symmetry breaking entails we must first define the notion of *symmetry* in physics. This is not so easy, for doing so properly requires some abstract mathematics, and there are examples of highly complicated symmetries in physics.[24] Let us therefore commence with a simple example: *translational symmetry*. A system exhibits translational symmetry if we can translate it - i.e. move it by a fixed distance - without altering the laws governing that system. By approximation this holds for small translations on the surface of the Earth in relation to the force of gravity: it does not matter where exactly one conducts an experiment, it will always yield the same outcome. If, for instance, one wishes to measure the period of a pendulum, it makes no difference where one puts it - in a city, on a hill etc. Again, this only holds by approximation, for if one puts the pendulum on a very tall mountain the strength of Earth's gravitational field will in fact change noticeably.

Another important symmetry is that of *time translation*, i.e. a shift in time. This is the symmetry that is responsible for conservation of energy, as mentioned in footnote 10. We expect an experiment to yield the same outcome regardless of whether it was performed yesterday or will be conducted tomorrow. The laws of nature do not change if time is shifted by a fixed number of seconds, minutes, hours etc. Yet another example is *rotational symmetry*, i.e. the invariance of a system under rotations by a certain angle. On the Earth's surface there exists, by approximation, a rotational symmetry around the vertical axis pointing towards zenith, as might be seen from the fact that a spinning top remains upright forever if there is no friction. This is different, however, if we consider rotations on Earth's surface along a horizontal, azimuthal axis, for then the direction of the gravitational field changes whenever we rotate.

In all these examples of symmetries, it seems that the only system that showcases them perfectly is the entire universe. This intuition was already expressed by Leibniz in his famous correspondence with Samuel Clarke.[25] Indeed, in his third letter Leibniz notes that it would not have mattered if God had changed East into West or created the universe a year sooner than He in fact did, or if the universe were rotated by 180 degrees.

---

[22] Katherine Brading, Elena Castellani, and Nicholas Teh, "Symmetry and Symmetry Breaking," in *The Stanford Encyclopedia of Philosophy*, Fall 2023, ed. Edward N. Zalta and Uri Nodelman (Metaphysics Research Lab, Stanford University, 2023), accessed January 27, 2024, https://plato.stanford.edu/archives/fall2023/entries/symmetry-breaking/.

[23] Franco Strocchi, "Spontaneous Symmetry Breaking in Classical Systems," *Scholarpedia* 6, no. 10 (October 7, 2011): 11195, accessed January 27, 2024, http://www.scholarpedia.org/article/Spontaneous_symmetry_breaking_in_classical_systems.

[24] Mirror symmetry for instance.

[25] Gottfried Wilhelm Leibniz and Samuel Clarke, *Leibniz and Clarke: Correspondence*, ed. Roger Ariew (Indianapolis: Hackett Publishing Company, 2000).

Nowadays we formalise Leibniz's ideas by saying that a physical system exhibits a symmetry if there is a certain operation (e.g. a space or time translation, or a rotation) that we can perform on the system without changing the laws describing said system. We then say that a symmetry is *broken* if the laws governing a system exhibit that symmetry, but the *state* of the system does not. Furthermore, we call an instance of symmetry breaking *spontaneous* if a system changes from a symmetric to an asymmetric state by itself, without external compulsion. As Gaudenzi explains: "the qualification *spontaneous* is key and is there to indicate that the breaking happens by itself; it is exclusively a consequence of the interactions internal to the physical system and not due to forces applied to it from the outside, a process, by contrast, which is called *explicit* symmetry breaking."[26] Thus, we see that symmetry breaking is called spontaneous in order to underscore a contrast with a non-spontaneous version of the phenomenon, which would be explicit symmetry breaking.

Since these definitions are rather abstract it is useful to consider a concrete example: that of a pencil with an infinitely sharpened tip standing exactly upright on a perfectly horizontal table. The laws describing this system, namely Newton's laws and the law of gravity, exhibit a rotational symmetry around the vertical axis. This can be seen from the fact that the energy of the system would not change if it is rotated around this axis, since the vertical axis aligns precisely with the direction of the gravitational field. If, now, the pencil really stands perfectly upright, then that state is also symmetric: we could rotate the pencil around the vertical axis without it falling down. In practice, however, we know the pencil will never remain upright indefinitely, but will fall to one side. When that happens the rotational symmetry is broken, for if we now rotate the fallen pencil around the original vertical axis we move it in a circle around its tip, thereby clearly changing the state of the system. This is an instance of *spontaneous* symmetry breaking since the upright pencil will fall to one side if it is influenced by an infinitesimally small disturbance (a *perturbation*): any outside interference, no matter how small, will bring the pencil out of its perfectly upright position. Such an infinitesimal perturbation will always be present in practice, thus causing the pencil to fall down without an apparent cause, i.e. spontaneously. The direction in which the pencil falls is absolutely unpredictable, since the necessary perturbation need only be infinitesimally small and could therefore come from a car driving by, a butterfly in China or even an event that occurred somewhere across the universe.

Yet it could be argued that the falling of the upright pencil is not truly spontaneous, since it can only happen by means of a perturbation - be it infinitesimal. There is therefore always some type of external stimulus causing the symmetry to break, even if that stimulus is in principle unknowable to us - the pencil does not *really* break its rotational symmetry by itself. Such an intuition was expressed by Pierre Curie in the form of a general principle: "when certain effects show a certain asymmetry, this asymmetry must be found in the causes which gave rise to it."[27] In other words: if a system exhibits a certain symmetry and that symmetry is broken, there must be a symmetry breaking cause (a perturbation).

Whereas Curie's principle appears valid in classical mechanics and raises the question of whether classical spontaneous symmetry breaking is truly spontaneous, it does not, at first sight, seem to

---

[26] Rocco Gaudenzi, *Historical Roots of Spontaneous Symmetry Breaking: Steps Towards an Analogy*, SpringerBriefs in History of Science and Technology (Cham: Springer International Publishing, 2022).

[27] John Earman, "Curie's Principle and Spontaneous Symmetry Breaking," *International Studies in the Philosophy of Science* 18, nos. 2-3 (July 1, 2004): 173–198.

apply to quantum theory. This might be illustrated by the classic example of spontaneous symmetry breaking in quantum mechanics: the ferromagnet.[28] We imagine such a magnet as consisting of a lattice of particles carrying a spin that can each point in any direction. It is energetically favourable for the spins to align, but it does not matter in what direction. In other words: the system exhibits a global rotational symmetry that rotates all spins by the same angle. Above a certain critical temperature, called the Curie temperature (again named after Pierre Curie), the thermal fluctuations in the magnet are stronger than the tendency of the spins to align, so the system will be disordered and non-magnetic. If, however, the system is cooled down below the Curie temperature, all spins spontaneously point in one (unpredictable) direction, giving rise to a net magnetic field. Since we are dealing with a quantum system, this symmetry breaking is usually thought of as arising due to a random "quantum fluctuation", therefore being truly spontaneous.

However, this common view must be critically questioned, for we know that, in the Copenhagen interpretation, the random "choosing" of a direction must ultimately be caused by either a perturbation[29] (in which case it is explicit symmetry breaking) or else a measurement. We thus arrive at the same conceptual issue as for spontaneous emission: can a quantum mechanical event really be called spontaneous if it is induced by a measurement? Is not the measurement a form of external stimulus that invalidates the spontaneity of the event?

3.3 Spontaneous collapse theories

From our investigation into spontaneous emission and spontaneous symmetry breaking we arrive at the conclusion that spontaneity in quantum systems exists only in a weakened form, since there must always be an external stimulus in the guise of a measurement or perturbation in order to induce the emission and symmetry breaking events. However, this conclusion is valid only if we assume the problematic Copenhagen interpretation, in which the precise nature of measurement remains enigmatic. There are alternative interpretations of quantum mechanics in which no measurement is needed for a wave function to collapse. A certain class of such interpretations is known as *spontaneous collapse theories* and we will study them now, since their name suggests that they entail some form of spontaneity. In examining spontaneous collapse theories we aim to answer the question: can quantum phenomena such as emission and symmetry breaking be said to be absolutely spontaneous in this interpretation?

To answer this question we must first examine the spontaneous collapse theories more closely. The most important aspect of these theories is the idea that wave functions collapse at random times and places without the need for something akin to measurement. The collapses occur all the time, but mechanisms are built into the theory to ensure that micropscopic systems rarely undergo wave function collapse, whereas macroscopic quantum systems collapse extremely rapidly, thereby behaving like stable, classical objects. There is also a version of the spontaneous collapse theories in which collapse events do not occur at discrete times and places, but continuously. This is known as the Continuous Spontaneous Localisation Model (CSLM), and it is modelled by adding a stochastic

---

[28] Brading, Castellani, and Teh, "Symmetry and Symmetry Breaking."

[29] Klaas Landsman, *Foundations of Quantum Theory*, vol. 188, Fundamental Theories of Physics (Cham: Springer International Publishing, 2017), Chapter 10.

field to the Schrödinger equation. The question which then arises is where this stochastic field itself comes from.

In the best known spontaneous collapse theory, the Ghirardi-Rimini-Weber (GRW) model - also known more generally as Quantum Mechanics with Spontaneous Localisations (QMSL),[30] two parameters are introduced to guarantee the right behaviour: f is the so-called *localisation frequency*, i.e. the average frequency with which spontaneous wave function collapse occurs, and d denotes the *localisation precision*, i.e. the scaling factor for the wave function when it undergoes collapse. At every spontaneous localisation event, a localisation operator is applied to the wave function in order to concentrate it in a smaller region. The probability of the localisation operator hitting at a specific position (in higher-dimensional configuration space, which includes the spatial coordinates) is proportional to the amplitude squared, i.e. the probability of finding a particle there. For the values $f = 10^{-16}$ s^{-1} and $d = 10^{-5}$ cm we get the following: "a microscopic system undergoes a localization, on average, every hundred million years, while a macroscopic one undergoes a localization every 10^{-7} seconds."[31] The proposed solution for the paradox of Schrödinger's cat is that "the cat is not both dead and alive for more than a split second."[32] Large objects, like a cat, do not exhibit any significant quantum behaviour because their wave functions collapse almost instantaneously, whereas microscopic entities may persist in their quantum states almost indefinitely because localisation events are so rare for them.

Of course, this raises the question of why it seems that wave function collapse is normally induced by the act of measurement. The role of measurement is incorporated and accounted for in the GRW theory as follows: whenever a microscopic quantum object is measured in the practical sense of e.g. bombarding it with photons (so *not* in the formal Copenhagen sense of projective evolution), then it becomes "part of" the macroscopic measuring device. In other words: there comes into being a correlation between the entity being measured and the measuring apparatus. But as we have seen, superpositions of macroscopic objects are supressed very quickly. The microscopic object that has become correlated to the measuring device through measurement is then implicated in this very rapid collapse, leading to the idea that measurement causes wave function collapse.[33]

The question that we should now ask ourselves is: to what extent do the collapse theories just outlined contain an element of true spontaneity? It seems that every localisation event in the spontaneous collapse theories is an instance of absolute spontaneity. These wave function localisations occur at random times and places and "out of the blue" - no external cause can be identified at all. In this way, spontaneous collapse theories embrace and postulate a ubiquitous and absolute spontaneity throughout the universe. If, then, such spontaneous localisation events lead to emission or symmetry breaking, then these are by extension truly spontaneous too. In that sense absolute, unrestricted spontaneity in quantum phenomena is only made possible by the implementation of spontaneous collapse theories and not in other interpretations of quantum mechanics.

---

[30] Giancarlo Ghirardi and Angelo Bassi, "Collapse Theories," in *The Stanford Encyclopedia of Philosophy*, Summer 2020, ed. Edward N. Zalta (Metaphysics Research Lab, Stanford University, 2020), accessed January 27, 2024, https://plato.stanford.edu/archives/sum2020/entries/qm-collapse/.

[31] Ghirardi and Bassi.

[32] Ghirardi and Bassi.

[33] Peter J. Lewis, "Collapse Theories," November 6, 2017, Preprint.

3.4 Back to history

Having studied a variety of appearances of spontaneity in physics, we now return once more to the philosophers from chapter 2 in order to draw some interesting parallels and to outline some main ways of thinking about the spontaneous. We repeat that it is not our aim to vindicate e.g. Lucretius by arguing that the Epicurean swerve foreshadows the spontaneous localisation of the GRW model. We wish to point out similarities in different conceptions of spontaneity, such that we can use those patterns as a basis for constructing a concrete and useful definition of spontaneity in nature that can be compared to similar concepts (which is what we aim to do in the next chapter).

3.4.1 Potentiality, actuality and spontaneity

The application of Aristotelian concepts to quantum theory is somewhat of a "tradition", going back at least to Heisenberg himself, who, in his 1958 *Physik und Philosophie* stated about particle creation:

> If we compare this situation with the Aristotelian concepts of matter and form, we can say that the matter of Aristotle, which is mere "potentia," should be compared to our concept of energy, which gets into "actuality" by means of the form, when the elementary particle is created.[34]

Note that this comparison is slightly ironic, since the Greek words for potentiality and actuality were *dunamis* and *energeia* respectively.[35] More generally, Heisenberg thought that "the transition from the 'possible' to the 'actual' takes place during the act of observation."[36] The wave function would then be the quantitative formulation of the Aristotelian concept of potentiality,[37] such that a quantum state is only actualised when measurement occurs. As Jaeger concludes: "thus, potentiality provides the relationship between the objective state of and the possible measured properties of a physical system."[38] This is of course very much in the Copenhagen spirit.

However, the comparison between quantum theory and Aristotle has been variously criticised.[39] Heelan even states that "the philosophical setting of Heisenberg's thought is so entirely foreign to that of Aristotle that it is scarcely worthwhile to compare them."[40] More specifically, it has been argued that Aristotelian concepts are inadequate in the context of quantum theory because of the total lack of a *teleological* significance to quantum potentiality.[41] Jaeger, on the other hand, develops the thesis that Aristotle and quantum mechanics show deep analogies, in particular with respect to spontaneity: "quantum potentiality has much more in common with *dunamis* than capturing the general indefiniteness of properties of the quantum system which, after all, is already captured by Heisenberg via a different notion, *Unbestimmtheit* (indeterminacy); in particular, it captures the

---

[34] Werner Heisenberg and F. S. C. Northrop, *Physics and Philosophy : The Revolution in Modern Science*, First Harper Torchbook edition, ed. Ruth Nanda Anshen, World Perspectives; v. 19 (New York: Harper & Row, 1962), p. 160.

[35] Kožnjak, "Aristotle and Quantum Mechanics."

[36] Heisenberg and Northrop, *Physics and Philosophy : The Revolution in Modern Science*, p. 54.

[37] Kožnjak, "Aristotle and Quantum Mechanics," p. 460.

[38] Gregg Jaeger, "Quantum Potentiality Revisited," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 375, no. 2106 (October 2, 2017): p. 2.

[39] Jaeger.

[40] Patrick A. Heelan, *Quantum Mechanics and Objectivity* (Dordrecht: Springer Netherlands, 1965), p. 152.

[41] Jaeger, "Quantum Potentiality Revisited."

aspect of spontaneous causation involved in quantum measurement."[42] To understand Jaeger's idea that the transition from potentiality to actuality in quantum measurement is best captured by the Aristotelian conception of spontaneity, let us recall Aristotle's definition of spontaneity from section 2.1: "hence it is clear that events which belong to the general class of things that may come to pass for the sake of something, when they come to pass not for the sake of what actually results, and have an external cause, may be described by the phrase 'from spontaneity'." By this definition, there is no teleological aspect to the way spontaneous events unfold, and they are externally caused. According to Jaeger, this fits with quantum measurement:

> Measurement, by contrast, can be considered a process in which potential being, the potential to be spontaneously actualized by an appropriate external influence, is actualized through *accidental efficient causation*, rather than by nature (again, with no role for *telos* or final cause); it is spontaneous motion within the Aristotelian approach to causation. Measurement coincides with an appropriate external interference with the natural motion of a system, preventing the change which would otherwise occur were it to remain isolated, that is, that described by the time evolution of state described by the Schrödinger law of motion.[43]

Yet, there is a crucial disanalogy: there is no *probabilistic* aspect to Aristotle's spontaneity at all. In fact, this lack of probability seems to result in an understanding of spontaneity in quantum mechanics that is the very opposite of the one we developed earlier in this chapter. By Jaeger's analysis, quantum measurement is in line with Aristotelian spontaneity because it is an external influence that disturbs a system's unitary evolution. But in our analysis, the external influence of measurement was precisely an obstacle to true spontaneity in quantum theory. We have instead sought to identify the spontaneous in quantum mechanics with its probabilistic aspect, and this is what is missing in the Aristotelian approach. This should not come as a surprise, for we already noted in section 2.1 that Aristotle's characterisation of spontaneity by way of external causation did not fit with our conception of spontaneity as an event without external stimulus. Of course, the fact that Aristotelian spontaneity does not fit well with our notion of spontaneity does not mean that Jaeger is wrong in making the comparison with quantum measurement as external disruption. Kožnjak, however, has in fact argued that Jaeger's comparison is inadequate.[44] It is not in our interest to delve any further into this discussion, for it has become clear now that Aristotle's conception of spontaneity is too far removed from the notion that we are aiming to characterise and illuminate in this thesis.

3.4.2 The swerve and localisation

Epicurean ideas, on the contrary, seem to be more readily of interest. Vavilov reminds us that "it would be a crude error to see in Epicurus and Lucretius precursors of quantum mechanics; yet it is impossible to consider this degree in which the antique idea coincides with the modern one as

---

[42] Jaeger, "Quantum Potentiality Revisited," p. 5.
[43] Jaeger, p. 11.
[44] Kožnjak, "Aristotle and Quantum Mechanics."

altogether fortuitous."[45] The swerve, of course, is especially relevant, as explained by Konstan: "the idea of such a minute veering, said to occur at no determinate time or place, is less strange in the modern age of quantum physics than it was in Epicurus' time."[46] In fact, Roman-Alcala has written an article dedicated entirely to the swerve in Epicurus, Lucretius and quantum mechanics.[47]

Yet, comparisons of this sort often misrepresent the basic tenets of quantum theory. Let us therefore ask to what extent the spontaneous *clinamen* really is comparable to the types of spontaneity in quantum theory that we have examined in this chapter. To answer this question it is important to clarify that, in the Copenhagen interpretation of quantum theory, there really is nothing akin to the Epicurean swerve. In popular science, a picture of quantum mechanics is often sketched in which particles vibrate and move about randomly and spontaneously, tunneling through barriers at undetermined times and places and even popping in and out of existence. One imagines, for instance, an electron orbiting a nucleus, and it is said that the electron might suddenly "decide" to jump to a lower or higher orbit. In such a picture, quantum theory really does look very swerve-like. The electron that, at random times and places, moves to another orbit, seems to be doing the same thing as Lucretius' atoms which, "at times quite uncertain and uncertain places [...] swerve a little from their course." A more advanced, but possibly even better example would be that of the random trajectories of particles in the path integral formalism: if a particle is emitted in a definite direction, it might not follow the expected classical path but instead "swerve" to end up somewhere else.

The problem, however, is that in such popular sketches of quantum behaviour the inevitable role of measurement in actualising all these phenomena is neglected. As explained in section 3.2, in the Copenhagen interpretation, any observation of "swerve-like" quantum behaviour can only come after measurement, implying that the spontaneous nature of the phenomenon in question is (partially) lost. If we emit a particle in some direction, the probability distribution describing the likeliness of finding it somewhere evolves unitarily (i.e. deterministically) - and no random swerve happens along the way - until a detector makes a measurement on the particle such that it is instantly localised at a particular place. In such a process we cannot say that the particle has spontaneously deviated from its regular trajectory like Epicurean atoms, for it is the act of measurement that externally forces the particle to "choose" a location. The only spontaneity present, then, is the "choice" of the particle where precisely to be detected after being compelled to make *a* choice. For this reason, the spontaneous *clinamen* really is incomparable to quantum theory in the Copenhagen interpretation.

A different picture emerges, however, if we assume a spontaneous collapse interpretation as in section 3.3. The localisation event is very swerve-like in the sense that it happens at random moments and places and violates the normal, lawful evolution of the wave function. In the specific case in which we consider a wave function on three-dimensional space without any other quantum numbers, i.e. on the configuration space $\mathbb{R}^3$, the analogy goes even further, for then a localisation event makes the wave function only *spatially* smaller, implying that, by Heisenberg's uncertainty relations, the momentum of the particle becomes more uncertain (the particle "swerves").

Thus, we see that, whereas the mechanics of the spontaneous swerve are very different from

---

[45] S. I. Vavilov, "Lucretius' Physics," *Philosophy and Phenomenological Research* 9, no. 1 (1948): p. 38.

[46] David Konstan, "Epicurus," January 10, 2005, accessed April 20, 2024, https://plato.stanford.edu/ENTRIES/epicurus/.

[47] Ramón Roman-Alcala, "Deviations and Uncertainty: the Concept of Swerve in Epicurus and Lucretius and Quantum Mechanics," vol. 1, Book 2, International Multidisciplinary Scientific Conference on Social Sciences and Arts-SGEM (Vienna, 2017), 225–236.

those of quantum theory in the Copenhagen interpretation, there is a real similarity with spontaneous collapse theories. In fact, the conception of spontaneity common to them seems to correspond to the active interpretation of deviation from law discussed in section 2.3, i.e. the occasional disruption, suspension or interruption of the ability of the relevant law to determine events. For the *clinamen* the disruption comes in the form of a slight deflection in a random direction, and for spontaneous collapse theories it is the localisation operator applied at random times and places. Of course, we should not conclude from this similarity that the Epicureans were somehow gifted with foresight that allowed them to invent quantum theory *avant la lettre*. Rather, the similarity points to a common way of understanding the concept of deviation from deterministic law, which is so general that it appears throughout the ages, irrespective of the precise physical worldview in which it is articulated.

3.4.3 Peirce and the laws of thermodynamics

The other, passive interpretation of deviation from deterministic law, however, seems to be a less universal idea and much more specific to Peirce - though he was of course led to it by the active interpretation of the Epicureans, as explained in section 2.3. In developing his ideas Peirce was greatly inspired by developments in statistical thermodynamics: in the derivation of the laws of thermodynamics from the assumption of random molecular behaviour he saw a model for the entire cosmos.

However, the relationship between Peirce's evolutionary cosmology and the first and second laws of thermodynamics is puzzling on multiple fronts. Peirce repeatedly praised the first law, even saying that "the discovery of this law is the greatest that science has ever made, and nothing that can be discovered hereafter (unless it be of a supernatural kind) can equal it."[48] Yet he also saw it as an obstacle to growth and increase in complexity, because *conservative* forces, i.e. forces for which there is no dissipation of energy, lead to *reversible* processes. Growth, Peirce thought, is an *irreversible* process and must come from evolution based on chance variations.[49] Peirce's solution was to reject the mechanistic determinism that he equated with the first law and instead assume the existence of absolute chance or spontaneity.

For the second law, things are different. In section 3.1 we gave the thermodynamic definition of a spontaneous process as one in which entropy increases, as the second law tells us must always be the case for the universe. Strangely, Peirce was not much concerned with this notion of spontaneity and the second law, as Reynolds writes: "one of the most striking things about Peirce's writings concerning his cosmological hypothesis is that when considering possible objections to it, he always concentrated on the first law of thermodynamics and never the second law."[50] This is strange because the second law actually seems to contradict Peirce's evolutionary cosmology. Universal growth, as we now understand it, would lead to *lower* entropy, against the second law. Peirce talks of the complete "crystallisation of mind" as the ultimate end of the universe, and this seems to be the very opposite of the inevitable "heat death" that the second law predicts.

The issue is further aggravated by Poincaré's famous *recurrence theorem*, which, roughly, states

---

[48] Andrew Reynolds, "Peirce's Cosmology and the Laws of Thermodynamics," *Transactions of the Charles S. Peirce Society* 32, no. 3 (1996): p. 406.
[49] Reynolds.
[50] Reynolds, p. 411.

that mechanical systems must return to their initial states infinitely often (*eternal recurrence*). Peirce's difficult dilemma is summarised by Reynolds:

> In fact Peirce is actually fighting two battles here: for one, he wants to say that on the whole the universe is evolving towards greater complexity, (i.e., he sides against the second law considered as a statement that the amount of order and complexity in the universe should ultimately decrease), and secondly he wishes to argue that, contrary to the notion of eternal recurrence, there will be a final end state from which there will be no departure (i.e., he sides with the second law as establishing irreversibility).[51]

The final state from which there is to be no departure must not be the heat death of the universe but the crystallisation of mind - a completely rational lawfulness of the cosmos in which any spontaneity has been turned into law. Therefore, Peirce's doctrine is not quite coherent: the second law and the crystallisation of mind simply do not go together. About this incoherence, Reynolds says that: "this may be because what we find in these writings of Peirce is not a finished product, but a work in progress. As a scientist he understandably wished to accommodate the important scientific principles of the time; yet as a visionary attempting to construct a new metaphysical theory which would serve as a guide to all future research, it was necessary to leave room for alterations."[52]

In conclusion, we now see that, although Peirce was inspired by thermodynamics, his conception of spontaneity was different from the thermodynamic definition. Spontaneity in thermodynamics is about what processes can happen by themselves, or, by the second law, what processes come with an increase in entropy. Peirce, on the other hand, conceives of spontaneity as absolute chance in the sense of deviation from law. His desire to invoke this spontaneity as a path to growth leads to a contradiction with the second law, but "absolute chance" does seem to foreshadow the quantum revolution that would already begin in the last years of Peirce's life.

3.4.4 Tychism in a quantum world

Thus, we arrive at the last part of our comparison between physics and the material from chapter 2: the relation between Peirce and quantum theory. Peirce died in 1914, nine years after Einstein's *annus mirabilis*, and could therefore have been familiar with at least the photoelectric effect and Planck's postulate of the quantised energy levels in black body radiation. However, Peirce spent his last years in poverty and complained bitterly that he could not get his hands on the latest scientific books and journals.[53] Thus, any link between tychism - which Peirce proposed before the turn of the nineteenth century anyway - and quantum theory is implicit in the sense that Peirce was not actually aware of quantum mechanics when he proposed the reality of absolute chance.

On the one hand, this makes it all the more incredible that Peirce was so bent on admitting pure chance, swimming against the current of a determinsitic *Zeitgeist*, when the quantum revolution would reverse that current so shortly afterward. Hartshorne, on the other hand, thinks Peirce should have anticipated more: "I find something pathetic in Peirce's failure to anticipate both basic aspects

---

[51] Reynolds, p. 417.
[52] Reynolds, p. 419.
[53] Reynolds, *Peirce's Scientific Metaphysics*.

of quantum physics, instead of only one of them. For he had all the conceptual tools needed for the second anticipation. Moreover, indicating the right direction for the development of physics was one of his professed ambitions and, he thought, a test of the soundness of his philosophy."[54] Here the first basic aspect refers to the probabilistic nature of quantum mechanics, and the second to its discontinuous, discrete "quantum" aspect. Mayorga, however, is kinder: "Charles Peirce was singularly poised to predict some of the 'metaphysical prejudices' about the world and how we know it, which quantum theory, developed just over a couple of decades afer Peirce, has revealed."[55] Mayorga also writes that "Peirce did not live to see the advent of the quantum revolution, but some of his philosophical speculations mirror the scientifc hypotheses that have been compared with observation in the context of quantum theory. I think Peirce would have been proud."[56]

But how similar are tychism and quantum theory really, when it comes to spontaneity? As explained in section 2.3, Peirce's spontaneity should be thought of as the passive interpretation of deviation from law: laws do not fully determine the course of events because the laws themselves are not quite "sharp". Practically speaking, this is precisely how the laws of quantum theory work out. Consider, for instance, a photon emitted by a light source moving toward a screen. Even if we know the initial direction of the photon very well, it may end up on the screen at a different spot than we would expect classically. Moreover, this place of detection on the screen will be random, though described by a specific probability distribution. In that sense, the laws of quantum theory do not rigidly fix the course of events that are to unfold but leave room for some indeterminacy and, possibly, spontaneity.

However, as we have repeatedly stressed, this is not precisely how the mechanics of quantum theory are usually understood, at least in the Copenhagen interpretation. Instead, we say the state of the photon evolves perfectly deterministically until it is measured by the screen, and only then is the photon forced to "choose" a precise position to actualise. The unitary evolution described by the Schrödinger equation leaves no room for deviation from law at all, but all of the randomness or chance is concentrated in the single event of measurement. Peirce speaks of spontaneity as a continuous deviation from law which is baked into those laws, with the laws actually becoming more and more rigid over time, and this picture is at odds with that of quantum mechanics, where evolution is deterministic except for measurement (in the Copenhagen interpretation). Nonetheless, on a more practical level, i.e. on the level of what an experimental physicist perceives in the laboratory, Peirce's tychism does apply quite well to describing quantum phenomena: the laws of quantum theory do not determine precisely when an atom will decay, in what direction a symmetry will break, or where a photon is detected. It is only when we scrutinise the precise mechanics of quantum theory that we see the dissimilarity between the Peircean and quantum conceptions of spontaneity.

Let us end this chapter by summarising our examples of the spontaneous. We first encountered Aristotle's definition, but this gives the wrong characterisation of the relation between quantum measurement and spontaneity. This chapter commenced with the study of spontaneous processes in thermodynamics, but these do not seem to exhibit fundamental spontaneity, which must come

---

[54] Charles Hartshorne, "Charles Peirce and Quantum Mechanics," *Transactions of the Charles S. Peirce Society* 9, no. 4 (1973): p. 196.

[55] Rosa Mayorga, "Scientific Pride and Metaphysical Prejudice: Ens Quantum Ens, Quantum Theory, and Peirce," in *The Oxford Handbook of Charles S. Peirce*, ed. Cornelis de Waal (Oxford University Press, February 19, 2024), p. 423-424.

[56] Mayorga, p. 437.

from a deviation from deterministic law. Such a deviation can be interpreted in the passive and active senses, of which the former is exemplified by Peirce’s tychism and possibly by the CSLM, and the latter by the Epicurean swerve and discontinuous spontaneous collapse theories such as the GRW model. All of these conceptions point to different nuances of the idea that something can happen *of its own accord*. In the next chapter, then, we will focus on the passive and active interpretations of deviation from law as definitions of spontaneity, and we will investigate how they incorporate randomness and indeterminism.

Chapter 4

Spontaneity, Randomness and Indeterminism

We have now reviewed a variety of examples of spontaneous events and processes, both in natural philosophy and in physics. Building on the knowledge we have thus gained, we turn to a more metaphysical study of spontaneity. In this chapter, we propose two theses about passive and active spontaneity respectively. Before we do so, however, we need to understand precisely what randomness and (in)determinism mean, for these are terms we use in our arguments. This is what sections 4.1 and 4.2 are devoted to. In section 4.3 we then propose our theses, argue that they fit well with many of the examples we have seen in chapters 2 and 3, and study the question of whether spontaneity actually exists in nature.

4.1 Chance and randomness

At the most basic level, randomness seems to be about a lack of pattern or predictability. It is at the heart of probability theory, the branch of mathematics that is concerned with *random variables*. The throwing of a die is, of course, viewed as the archetypal random event: once *alea iacta est* we can only hope for the best outcome, which is supposedly determined "by chance".[1] Now, chance and randomness are often equated, especially in science.[2] For instance, Landsman states:

> Though he did not mention it himself, randomness seems a prime example of a phenomenon Wittgenstein would call a 'family resemblance'. Independently, as noted by historians Lüthy and Palmerino on the basis of examples from antiquity and medieval thought, the various diferent meanings of randomness (or chance) [!] can all be identifed by their antipode.[3]

Lüthy and Palmerino similarly explain that: "as far as everyday language is concerned, our terms strongly overlap. Phrases such as 'I met him by chance,' 'this was an extraordinary coincidence,' 'I was randomly chosen,' or 'I was lucky enough to escape' all gesture at the fact that we couldn't have

---

[1] In reality, however, the throwing of a die or the tossing of a coin do not exhibit true chance, since the outcomes are determined by the initial velocity and rotation, the wind etc.

[2] Eagle, "Chance versus Randomness."

[3] Landsman, "Randomness?," p. 63.

predicted what in fact happened to us or to someone else."[4] These quotations exemplify the usual interchange of chance and randomness, which has led Eagle to identify it as a thesis:

> **Commonplace Thesis:** Something is random if and only if it happens by chance.[5]

Here chance means something along the lines of "single-case objective probability."[6] An event occurs by chance if it is the result of a trial with several genuine possibilities, each occuring with some frequency when the trial is repeated in the same fashion. For a fair coin toss, the two genuine possibilities would be heads (H) or tails (T), each occuring with a probability of 0.5. On the other hand, randomness, in its precise mathematical formalisation, is about the structure of a sequence of outcomes. For instance, if a fair coin toss yields a string[7] of outcomes

$$\text{HTHHTTHHHTTTTHHTHHTHTH},$$

then this looks random, since there is no discernable pattern. The string

$$\text{HHHHHHHHHHHHHHHHHHHH},$$

on the contrary, does not look random at all. If we throw heads so many times in a row we suspect the coin to be rigged in order to always land with heads on top - that is, we suspect that the outcome does not actually come about by chance.

The basic intuition behind the Commonplace Thesis is therefore quite clear: if an outcome of a trial comes about by chance and the trial is repeated to form a sequence of outcomes, then we expect this sequence to be random. Conversely, if a sequence of outcomes looks random, then surely it must have come about by a chance process, for how else could it have come to appear so disordered? This intuition is made precise in the more refined version of the Commonplace Thesis:

> **Refined Commonplace Thesis:** An outcome happens by chance if and only if, were the trial which generated that outcome repeated often enough under the same conditions, we would obtain a random sequence including the outcome.[8]

Eagle, however, argues that the Commonplace Thesis - even if it is refined - does not hold, on the basis of several counterexamples.[9] The first, and probably the most obvious, counterexample is that of unrepresentative outcome sequences that may come about by chance without being random. Suppose we toss a fair coin 1000 times. Then there is a real possibility - albeit an unlikely one - that we obtain 1000 heads. In fact, the probability for that to occur is

$$\left(\frac{1}{2}\right)^{1000} = \frac{1}{2^{1000}} \approx \frac{1}{1000^{100}} = \frac{1}{10^{300}}.$$

This is certainly a small number, but it is nonzero and an outcome string of 1000 heads is therefore not impossible. But such a string of 1000 heads is not at all random, as can be seen from the fact that we can describe it so easily with the phrase "1000 heads" instead of *actually* writing down

---

[4] Lüthy and Palmerino, "Conceptual and Historical Reflections on Chance (and Related Concepts)," p. 10.
[5] Eagle, "Chance versus Randomness."
[6] Eagle.
[7] A string is just a finite sequence.
[8] Eagle, "Chance versus Randomness."
[9] Eagle.

HHHHHHHHHHHHHHHHHHHHHHHHHHHH...HHHHHHHHHHHHHHHHHHHHHHHHHH,

where the three dots denote “many heads” (the other nine hundred something). This idea of being able to describe a sequence in a much shorter way than actually writing it down, is at the heart of the mathematical definition of “true randomness” of sequences, called *1-randomness*. A sequence is 1-random if it is the shortest computable description of itself, i.e. if it is *incompressible*. Equivalently, we can characterise a 1-random sequence as one that is *patternless* or *unpredictable*[10] - one cannot succesfully bet on the next digit based on knowledge of the previous ones.[11]

Against Eagle’s counterexample we can argue that, from a probabilistic trial, we are far more likely to obtain a random sequence than a non-random one. Thus, although there might be atypical, non-random outliers, there are so few of those that we can discard them and retain the Commonplace Thesis. This idea can be made mathematically precise with the concept of *typicality*,[12] or by noting that, in the limit of a countably infinite number of trials, the non-random sequences of outcomes form a “set of measure zero”, i.e. a set of zero probability.

Eagle also provides counterexamples to the refined Commonplace Thesis that allegedly exhibit randomness but no chance, such as chaotic systems. Surely such examples can again be objected to, but it is beyond our scope to go into this any further. Instead of trying to show that chance and randomness are equivalent, let us take Landsman’s approach of accepting that different forms of chance and randomness show a family resemblance. In particular, let us examine the members of this random family in the context of quantum theory.

According to Landsman, the family of conceptions of randomness is of a special kind: “I submit that randomness is not just any old Wittgensteinian family resemblance, but a special one that is always defined *negatively*.”[13] In other words: randomness is always characterised by what it is *not*, as seen from the mathematical definitions of *in*compressibility, pattern*less*ness and *un*predictability. To support this claim Landsman provides an extensive list of examples, including many of the ones we have studied in this thesis. In Aristotle’s example of a man who goes to the market and meets his debtor there, the randomness (or properly translated: spontaneity) comes from the fact that he did *not* go there to meet his debtor, but for a different purpose.[14] Similarly, Lucretius’ account of the Epicurean swerve is marked by the fact that the atoms do *not* follow their natural straight course.[15] Landsman gives further examples from biology, philosophy, mathematics, and, of course, quantum physics. What, then, are the antipodes of randomness in quantum theory? Landsman writes:

> The antipode defining which particular notion of randomness is meant may vary even within quantum mechanics, and here two main candidates arise: one is determinism, as emphatically meant by Born and most others who claim that randomness is somehow ‘fundamental’ in quantum theory, but the other is compressibility or any of the other equivalent notions defning what is called 1-randomness in mathematics as its antipode.[16]

In other words: one conception of randomness in quantum physics is the overwhelmingly likely

---

[10] Landsman, “Randomness?,” Theorem B.1.

[11] In mathematical parlour, the relevant characterisations of 1-randomness are known as Kolmogorov-Chaitin randomness, Martin-Löf randomness and Schnorr randomness.

[12] Klaas Landsman, “Typical = Random,” *Axioms* 12, no. 8 (8 2023): 727.

[13] Landsman, “Randomness?,” p. 63.

[14] Landsman, p. 63.

[15] Landsman, p. 64.

[16] Landsman, pp. 62-63.

1-randomness of a sequence of outcomes of quantum measurements as specified by the Born rule,[17] and the other is indeterminism. Landsman has in fact leveraged this distinction to argue that Bohmian mechanics[18] cannot be deterministic if it is to reproduce the Born rule, since a deterministic theory can never reproduce the 1-random sequences of quantum measurement outcomes that one obtains from the Born rule.[19]

4.2 Causal (in)determinism

But what, precisely, is meant by this antipode of quantum randomness known as *determinism*? Generally speaking, determinism is the idea that every event in the world is fully determined, in the sense of being necessitated by antecedent events and conditions together with the laws of nature.[20] It is the *Doctrine of Necessity* that Peirce thought so unreasonable. In a deterministic world, the state of the universe at a time t_0 completely determines the state of the universe at any other time. Discussions of determinism rarely fail to mention *Laplace's demon*, a godlike being imagined by Laplace who has such perfect knowledge of the universe and such unlimited computing power that it can predict both the past and future from the present.

Of course, there is a host of issues with the definition of determinism just given. What do we mean by "the world" and by "laws of nature"? How do we define "the world at time t_0" or even just "the present"? We know from the theory of general relativity (GR) that this last point is not at all straightforward. Still, it is often thought that classical physics, including GR, is perfectly deterministic, whereas quantum mechanics is highly indeterministic. This is, however, false. There are indeterminstic aspects to GR, especially where *singularities* are concerned. Paths (geodesics) through spacetime ending in a singularity can, by definition, not be extended arbitrarily into the future, implying that the fate of things moving on those paths is undetermined beyond the singularity. Quantum mechanics, on the other hand, is in some ways more determinstic than classical physics.[21] Indeed, the unitary "Schrödinger" evolution that we have discussed at length in chapter 3 is in a sense the most perfect form of determinism that exists - it conserves all information, both into the future and the past. This fact is at the origin of the black hole information paradox, which arises from the question of how unitary quantum evolution can be squared with the apparent loss of information of something thrown into a black hole.

But, when looking for examples of indeterminism in physical theories, we apparently do not even need to resort to modern physics. There is a famous thought experiment known as *Norton's Dome*,[22] in which one imagines a dome which is shaped in such a way that, if one rolls a ball up the dome from one of the sides at the right speed, it stops precisely at the apex *in a finite amount of time*. The entire system is assumed to be governed by Newton's laws of motion, and since Newton's

---

[17] The Born rule states that the probability of finding a quantum system in a given state when performing a measurement equals the square of the wave function in that state.

[18] Bohmian mechanics, also known as pilot wave theory, is an interpretation of quantum mechanics that originated with David Bohm and which is usually viewed as an attempt to make quantum mechanics deterministic.

[19] Klaas Landsman, "Bohmian Mechanics Is Not Deterministic," *Foundations of Physics* 52, no. 4 (2022): 1–17.

[20] Hoefer, "Causal Determinism."

[21] John Earman, "Determinism: What We Have Learned and What We Still Don't Know," in *Freedom and Determinism*, ed. Joseph K. Campbell (Bradford Book/Mit Press, 2004), 21–46.

[22] John D. Norton, "Causation as Folk Science," *Philosopher's Imprint* (Ann Arbor, MI) 3, no. 4 (November 1, 2003); John D. Norton, "The Dome: An Unexpectedly Simple Failure of Determinism," *Philosophy of Science* 75, no. 5 (2008): 786–798.

laws are invariant under time-reversal, the fact that there is a solution in which the ball rolls up and remains motionless at the apex implies that there is also a solution in which the ball stands still at the apex and, after some amount of time, spontaneously rolls down in some direction. Van Strien has shown that the idea of Norton's dome actually already existed in the nineteenth century work of Boussinesq - in fact, Norton's dome is a special case of Boussinesq's dome.[23]

Norton's dome looks like an example of spontaneous symmetry breaking in classical mechanics. After all, the dome is rotationally symmetric. Should we conclude, then, that indeterminism exists in Newtonian physics and in fact provides an example of spontaneity and more specifically of spontaneous symmetry breaking? Not necessarily, for there are issues with Norton's thought experiment. A major one is the fact that the (gravitational) force acting on the ball does not satisfy the mathematical condition of Lipschitz continuity, which is normally used to prove the uniqueness of solutions to (Newton's) equations.[24] However, Norton's dome is interesting because it provides us with a new possible characterisation of spontaneity as indeterminism. The ball can roll down spontaneously precisely because of the alleged indeterminacy in Newton's laws. We will return to this idea in the next section.

To conclude this section, let us consider the relation of (in)determinism to chance and randomness. It is clear that a genuinely probabilistic process leads to a failure of determinism (although the probability distribution must be non-trivial,[25] i.e. must not just assign the values 1 and 0 to outcomes). After all, if an outcome comes about by "real" chance, then the world could evolve in different ways from the same conditions, according to the various outcomes with non-zero probability. Conversely, however, it does not seem to be the case that indeterminism must ultimately come from some "fundamental chance", as exemplified by singularities in GR, where indeterminism does not arise from any probabilisitic process, but rather from the end of spacetime itself.

The relation of randomness to determinism seems yet more complex. Although 'random' and 'indeterministic' are often used interchangeably, it is not even clear that randomness implies indeterminism. Indeed, one can construct non-computable functions in mathematics, such that when physical theories are devised in which a system's evolution is deterministically described by such functions, one obtains a random sequence of outcomes.[26] Against such examples, however, one could argue that the laws of our best physical theories probably do not make use of such exotic functions and that the counterexample is therefore too far-fetched. Still, it shows that randomness and indeterminism are not necessarily equivalent.

4.3 Spontaneity and time

Having introduced the concepts of chance, randomness and (in)determinism, we can finally turn to our ultimate aim of characterising spontaneity in nature. We want to understand what it would mean for a natural entity to do something *sponte sua*, of its own, without external stimulus.

---

[23] Marij van Strien, "The Norton Dome and the Nineteenth Century Foundations of Determinism," *Journal for General Philosophy of Science / Zeitschrift für Allgemeine Wissenschaftstheorie* 45, no. 1 (2014): p. 177.

[24] Mathias Frisch, "Causation in Physics," in *The Stanford Encyclopedia of Philosophy*, Winter 2023, ed. Edward N. Zalta and Uri Nodelman (Metaphysics Research Lab, Stanford University, 2023), accessed May 11, 2024, https://plato.stanford.edu/archives/win2023/entries/causation-physics/.

[25] Hoefer, "Causal Determinism."

[26] Eagle, "Chance versus Randomness."

Now, at first sight, there is no relation between spontaneity and randomness or indeterminism. After all, we can very well imagine an isolated entity governed by deterministic laws yet doing something of its own accord. Here we can go back to thermodynamics for an example: imagine an isolated box containing a gas in the left side of the box only. If we leave this box without performing any external stimulus on it whatsoever, the gas will spontaneously spread out to the right half of the box, thereby increasing its entropy. Such a process is perfectly spontaneous, since no external influence compels it to occur.

Yet, this example does not seem to showcase *fundamental* spontaneity, since the gas particles are governed by Newton's laws, and these laws are ultimately the cause of the process. The gas particles do not do anything *sponte sua*, but only behave under the jurisdiction of natural law. We therefore see that true spontaneity in nature must not only exclude external stimulus by other natural entities, but must also preclude the hegemony of the laws of nature. If an event is to occur truly, fundamentally spontaneously, then it must do so through a deviation from the relevant laws of nature. An entity showcasing spontaneous behaviour must, to some extent at least, release itself from the dominance and oppression of law. Thus, spontaneity implies indeterminism, as was the reason for introducing it in the first place for Lucretius and Peirce.

4.3.1 Passive spontaneity

But, in section 2.3, we have seen that there are two ways of understanding spontaneity as deviation from law: the active and passive interpretations, corresponding respectively to rigid and non-rigid laws. In the passive interpretation, spontaneous behaviour originates from the fact that the laws of nature themselves do not fully determine the course of events. Imagine, for the sake of argument, that the trajectory followed by a projectile launched from a cannon is spontaneous in this passive sense. This would mean that if we fix the cannon at a certain angle, and use the exact same amount of gunpowder every time, the projectile would still land at different places. Suppose, now, that the deviation from the mean distance from the landing place of the projectile to the cannon does not come from any external circumstance (the wind, the shape of the projectile etc.), but arises simply because the laws of mechanics are not fully rigid. The projectile would then deviate from the expected mean path *by itself*, i.e. spontaneously. Yet, this spontaneity would not occur at a specific time and place, but continuously along the entire trajectory. In the passive interpretation, then, spontaneity is the extent to which the behaviour of a natural entity continuously deviates from the expected mean evolution described by non-rigid laws of nature.

Now, when conceiving of non-rigid laws of nature, we most likely visualise a distribution in space, like for the cannon projectile mentioned above. However, we could also ask whether such non-rigidity of laws could manifest itself not only in space but also in time. That is: can we imagine that the laws describing *when* an event will occur are non-rigid? Or should we ascribe such a temporal deviation to spatial causes, e.g. to a difference in launching angle? It is not so difficult to imagine a non-rigidity in the laws determining *where* the projectile will land, but can we conceive of a fundamental non-rigidity in the laws determining *when* the projectile will land, which does *not* ultimately derive from spatial non-rigidity? Or is it because of the very way we think of natural laws that it is difficult to conceive of such non-rigidity in time? We imagine the laws of nature as describing the evolution of a system at one point in time to another, such that any question of *when* an event occurs is ultimately determined by the behaviour of the system at every infinitesimal point in time. Time is then assumed to continuously "flow" at the same "rate", such that a state can be evolved into the future by means of partial differential equations. This leads to our first thesis.

> **Passive spontaneity thesis (PST):** Assuming time to be a continuum and the laws of nature to exist only as a description of how a system evolves from one time to another, spontaneity in the passive sense, i.e. the inability of laws to fully determine the course of events, ultimately cannot exist as indeterminacy in time but only in (phase) space.[27]

Here we have allowed for space to be understood more broadly as *phase space*, which is the mathematical space of all possible states of a system. It consists of the space of coordinates, called configuration space, and the changes in time of those coordinates (more precisely: the momenta for those coordinates). For a single particle, the phase space is six-dimensional: three position coordinates and three velocity (momentum) coordinates.[28]

The PST may be counter-intuitive. There seems to be no reason why one cannot conceive of an event that occurs at an indeterminate time. What we are arguing, however, is that, because of the very way we think of natural laws, such an indeterminacy cannot be fundamental but must derive from other indeterminacies which exist in (phase) space. Let us first give a structured argument in favour of the PST and then consider the example of Norton's dome.

Indeed, suppose an event E is brought about at a time t_E from an earlier event E_0 at time t_0 by a set of non-rigid laws in the sense described in the passive spontaneity thesis, i.e. prescriptions of how the system in question evolves from one time to another. Since we assume time to be a continuum, we can divide it into infinitesimal pieces dt. At every moment t, the laws tell us how the system will look at a time $t + dt$. However, since the laws are not fully rigid, they give different possible states at $t + dt$. Yet, there is no variance in the time at which the new state has infinitesimally evolved from the previous one: the time difference is always dt. This is implicated in the very way we think of the timeline as a continuum and of the flow of time as always occuring "at the same rate",[29] an idea that can be compared to the Scholium of the *Principia* in which Newton states that "times passes equably."[30] Now, to determine the possible states of the world at t_E, we *integrate* over all the infinitesimal pieces of time dt. The various possible events at t_E resulting from E_0 are then obtained by considering all the possible paths that can be formed by concatenating all the possible infinitesimal evolutions permitted by the non-rigid laws at all times $t_0 < t < t_E$. Thus, if the event E is among the possible events at t_E resulting from this procedure, then there is no fundamental indeterminacy in the time at which E occurs, since this time is obtained by integrating over all infinitesimal pieces dt. This picture of the way the course of events unfolds is very similar to

---

[27] For a quantum system, we should consider a *Hilbert space* instead of phase space. Indeed, the core idea of *quantisation* is to construct a Hilbert space out of a classical phase space.

[28] In mathematical physics, a solution to the equations of motion is modelled as a trajectory in phase space. To see that it is important to take this into account, imagine a particle confined to move in one dimension, such that its speed is undetermined. Then it would arrive at a specified point at an undetermined time. Still, this indeterminacy in time ultimately arrives from the indeterminacy in velocity, which is a spatial indeterminacy in the more general sense of phase space, such that it does not contradict the PST.

[29] Time seems, by definition, to always flow with one second per second.

[30] Robert Rynasiewicz, "Newton's Views on Space, Time, and Motion," in *The Stanford Encyclopedia of Philosophy*, Spring 2022, ed. Edward N. Zalta (Metaphysics Research Lab, Stanford University, 2022), accessed May 28, 2024, https://plato.stanford.edu/archives/spr2022/entries/newton-stm/.

what in physics is called the *path integral*.

It appears that the only way in which passive spontaneity could exist in the guise of fundamental non-rigidity along the time axis, would be through an exotic form of causality or natural laws in which causes do not necessarily determine their effects at the very next moment, but possibly a little later of earlier. However, this seems to fundamentally contradict the very way the human mind conceives of the flow of time, or, more generally, of *becoming*. How can an effect follow its cause any earlier than *at the very next moment*? And if an effect does not immediately follow its cause, then what happens in the mean time?

To make our ideas more concrete, let us consider Norton's dome from section 4.2, since it seems to be a counterexample to the PST. Indeed, if we accept it as a valid thought experiment for the sake of argument, then it seems to show us spontaneity in the passive sense not only in the "choice of direction" in which the ball moves down the dome, which is a spatial indeterminacy in the laws, but also in the undetermined moment at which the ball starts to move at all. However, we must be very careful here, for we are in fact introducing a teleological thinking that contradicts the assumption about the form of natural law in the PST. To see that we are inclined to think teleologically, note that in Norton's thought experiment one considers solutions to Newton's laws which are valid over an extended period of time, or even all of time. One thus studies the behaviour of the ball by considering what it has done in the past and what it will do in the future - one assumes a godlike perspective "outside of time", along the lines of what is called the *principle of least action* in physics.[31] If, instead, one remains faithful to the conception of natural law outlined in the PST, then one must understand the spontaneous movement of the ball as follows: at a time t_0 it is motionless at the apex of the dome, and its possible trajectories are found by considering, at every instant of time after t_0, the possibility of the ball remaining still and the 360 degrees of possibilities of it moving off in some specific direction. This "choice" is made anew and anew by the ball at every instant of time, and by concatenating all such possible choices one finds all the possible paths, i.e. the boring path of the ball remaining still by always "choosing" to do so, and all the other paths which are specified by a moment and direction of spontaneous movement. Ultimately, however, the indeterminacy in the moment at which the ball moves comes from the non-rigidity of the laws in phase space, which persists until the ball starts moving.

Now, the PST is important because, intuitively, spontaneity seems to *need* randomness in time. Suppose an event occurs spontaneously, but the time at which the event occurs is fixed. Then apparently, the event did not come about completely spontaneously, because there were laws governing when it should take place. Only after this time has been specified is the entity in question "allowed" to decide what exactly to do. This is the same pattern of thought that we encountered in quantum theory: in the Copenhagen interpretation, an event can only exhibit indeterminism when a measurement is performed, such that the measurement becomes the external stimulus prohibiting the true spontaneity of the event. Yet, in the passive interpretation of spontaneity, the necessity of randomness in time disappears because the required deviation from law occurs *continuously*. Thus, an entity being governed by non-rigid laws deviates from those laws *all the time* - it is not forced to deviate at a specific moment and its behaviour can therefore be said to be truly spontaneous.

---

[31] Vladislav Terekhovich, "Metaphysics of the Principle of Least Action," *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 62 (May 1, 2018): 189–201.

In terms of the examples considered throughout this thesis, only the Continuous Spontaneous Localisation Model (CSLM) seems to be comparable to spontaneity in this passive sense.

4.3.2 Active spontaneity

Things are different in the active interpretation of deviation from law. In that case, the laws of nature are understood to be fixed, with “swerves” occurring occasionally. We have argued in this thesis that this is, in a sense, the archetypal conception of spontaneity, found in Epicurean thought, spontaneous collapse theories, and possibly even in the notion of a miracle in religions such as Christianity. However, we will argue now that, if the active interpretation of deviation from law is to be an instance of true spontaneity, then the violation or swerve must occur *randomly in time*. More precisely, we will now argue for the following idea:

> **Active spontaneity thesis (AST):** Spontaneity in the active interpretation of occasional deviation from rigid laws is equivalent to the existence of events, not under any external stimulus, that occur at random moments in time.

Here, we mean by ‘random’ the notion of chancy, probabilistic randomness expressed by the Commonplace Thesis (ignoring the subtleties discussed in section 4.1), and it is understood that the ‘randomness in time’ must not come from some external source but only from the entity involved in the event.

To argue for the validity of the AST we need to demonstrate two things: that events occurring at random moments are spontaneous, and the contrapositive, i.e. that spontaneity in the active sense must always imply such randomness in time. The first is straightforward: if an entity undergoes an event at a random moment in time without that moment being determined by anything external, then the specification of the moment at which the event occurs can only come from the entity itself and the (rigid) laws governing it. Yet, since the event in question occurs at a random moment, no rigid law can cause it. This means that the entity involved undergoes the event of its own accord, i.e. *sponte sua*.

To demonstrate the contrapositive, assume we have a system governed by rigid laws with occasional spontaneous events in which those laws are violated. By means of a proof by contradiction, suppose the times at which the deviation events (the “swerves”) occur are fixed by the laws. An entity involved in a deviation event then determines only *how* it violates the laws, but not *when*. This means that it cannot fully cause its own deviating behaviour, for it can only “swerve” when that swerve is caused - in the sense of being determined to occur - by the laws governing the entity. The violation events are therefore not fully *sua sponte*, contradicting our original assumption of the existence of occasional spontaneous events. We conclude that true, complete spontaneity in the active interpretation must always come from events that occur randomly in time.

The conception of spontaneity propounded in the AST fits well with both the Epicurean swerve and the spontaneous collapse interpretations of quantum mechanics. It also explains why, in the Copenhagen interpretation, there are no truly spontaneous events: all randomness in the Copenhagen interpretation comes from measurements, but these always occur at specific moments, such that the randomness exists only in the possible measurement outcomes *at a given time*, and not in *when* the measurement is performed. This is "baked into" the Hilbert space formalism of quantum mechanics.[32] If a system is measured by a measurement apparatus, then the apparatus is an external stimulus. If a system "measures itself"[33] (if this is even possible), then there is no randomness in the time at which the measurement occurs, meaning, by the AST, that there is no true spontaneity.

In conclusion, we find two appropriate characterisations of spontaneity in nature, which both imply indeterminism:

- Spontaneity in the passive sense of non-rigid laws, allowing entities to deviate from the mean continuously of their own accord, but precluding a fundamental randomness in time.
- Spontaneity in the active interpretation of occasional swerve-like violations of otherwise rigid laws. For these deviation events to be truly spontaneous, they must occur at random times.

A natural question is now: does spontaneity exist in our universe? Restricting our attention to quantum theory, which is the most promising place to look for fundamental spontaneity in our world, the answer seems to depend very much on one's interpretation of quantum mechanics. This is actually an important justification for the very study of spontaneity as a way to probe the foundations of physics. Whereas the question "does randomness exist?" is answered positively for both the Copenhagen interpretation and spontaneous collapse theories, the question "does spontaneity exist?" is, at least in this respect, more refined and can distinguish between these two interpretations of quantum theory. After all, this latter question is answered by a resounding "yes!" for spontaneous collapse theories, but by something like "no, not *really*" for the Copenhagen interpretation. One of the major aims of this thesis was to argue for the interest of the concept of spontaneity, besides randomness and determinism, in understanding our best physical theories. It seems that this aim has been achieved.

---

[32] The axioms of quantum mechanics posit a Hilbert space of states describing a system at any particular instant of time. Time evolution is then generated by the Hamiltonian. In the Copenhagen interpretation, measurement is modelled as a positive operator-valued measure (POVM) on the Hilbert space. Thus, the very structure of the axioms prescribes that measurements occur at single moments in time. It would be interesting to compare this to the relativistic case.

[33] The idea of a system measuring itself seems to fall outside the Copenhagen interpretation because it would violate the *Heisenberg cut*, i.e. the interface between the classical observer and the quantum wave function.

Chapter 5

Conclusion

Studying spontaneity in nature amounts to examining whether anything in the world can happen *of its own accord*, without outside compulsion. It is, in a way, quite natural to ask this question. Everywhere around us, we see the law of cause and effect determine the course of events. At the same time, there are many things that appear to just happen, without any apparent reason. Pondering the spontaneous then amounts to asking whether these phenomena will, if we just look well enough, turn out to have happened because of some external stimulus after all, or simply *by themselves*.

It is no wonder, then, that the ancients were already concerned with spontaneity. In chapter 2 we saw that Aristotle developed an elaborate theory of *to automaton*, and that the Epicureans saw themselves forced to introduce an element of spontaneity into their cosmos in order to rule out absolute determinism, as immortalised by Lucretius.

With the advent of physics as a modern science and the accompanying mechanistic philosophy, a worldview arose in which everything is determined by natural law. Against this doctrine of necessity, Peirce developed his tychism towards the end of the nineteenth century. He embraced the existence of absolute spontaneity and thought it was able to explain something that determinism could not: the very existence of laws themselves. In the law of large numbers and the central limit theorem, Peirce saw a model of how pattern and law may emerge from non-law or pure chance.

Only a few years later an unprecented revolution occured in the physical sciences: quantum mechanics was invented and became the most successful theory in the history of physics, if not the history of all of science. In the quantum world, chance seems to abound, and various phenomena are labelled as spontaneous by physicists, as described in chapter 3. Yet, all of this is already very well-known in the philosophical discussions on chance, randomness and (in)determinism. What, if any, is the added value of focusing on that one word ‘spontaneous’?

Arguing that there is in fact such an added value was the aim of chapter 4. There, we proposed two conceptions of spontaneity in nature: a spontaneity that originates in the laws of nature themselves not being fully rigid, and, secondly, an occasional, swerve-like deviation from otherwise wholly deterministic laws. One could of course ask why we should not consider a third option that combines the two, i.e. a continuous deviation from otherwise rigid laws. This, however, just comes down to the same thing as the first option: there does not seem to be any difference in saying that the laws of nature themselves are not rigid but vary around a mean value (which would be obtained by repetition of the process in question), and saying that the laws are in fact rigid but that there is a continuous deviation from those laws.

Our first, passive conception of spontaneity was greatly inspired by Peirce. The only theory in physics that seems to be in line with it is the continuous version of spontaneous collapse theories mentioned in section 3.3, i.e. the Continuous Spontaneous Localisation Model (CSLM). We argued for the Passive Spontaneity Thesis, which states that non-rigidity of laws of nature is ultimately conceivable only in phase space but not in time.

Our second, active conception of spontaneity seems to be the archetypal notion, in line with our everyday intuition and exemplified both the Epicurean swerve as well as the most common versions of spontaneous collapse theories, such as the GRW model. It corresponds to an idea that is more than just a family resemblance, the common core of meaning across varying examples being that of occasional violations of otherwise rigid deterministic laws. We proposed the Active Spontaneity Thesis, stating that active spontaneity is in fact equivalent to the existence of events which occur at random moments in time. In this view, spontaneity can be thought of as the absolutely patternless, unpredictable moment at which events occur.

Both ideas of spontaneity clearly imply indeterminism, but they are not just “mere indeterminism”. Spontaneity is something more specific, namely the existence of events that occur *by themselves*, or, in the words of Beethoven:

> Was Sie sind, sind Sie durch Zufall und Geburt, was ich bin, bin ich durch mich.

As such, different interpretations of quantum mechanics can be distinguished by whether they contain real spontaneity or not, as we argued in chapter 3. This is where the true interest of studying spontaneity in nature lies, in my opinion. It can be used to probe our best theories of physics in a new way. It provides us with a new angle to look at those theories, by asking: does this theory exhibit real spontaneity?

Indeterminism is a very broad term. The general theory of relativity is indeterministic, at least when singularites and black holes are involved. Yet there seem to be no spontaneous events in GTR. Similarly, randomness is a broad concept - although it can be made quite precise mathematically, as discussed in section 4.1. Many interpretations of quantum physics exhibit randomness, but this is not the case for spontaneity. Nothing happens truly spontaneously in the Copenhagen interpretation because of the inevitability of measurement for deviating from deterministic evolution. Spontaneous collapse theories, however, live up to their name.

Thus, if we want to better understand what our physical theories say about the workings of the world, about profound philosophical issues like causality or the predetermination of everything that happens in nature, then it may be worthwhile to add spontaneity in the specific sense outlined in this thesis - so not just as another of those words that might be used interchangeably with chance and randomness - to our conceptual toolbox. If this suggestion seems plausible, then the central aim of this thesis has been accomplished.

Bibliography

"This Month in Physics History: Einstein Predicts Stimulated Emission." *American Physical Society News* 14, no. 8 (2005).

Aristotle, Barnes, and Jonathan. "Complete Works of Aristotle, Volume 1 : The Revised Oxford Translation." In *Complete Works of Aristotle, Volume 1 : The Revised Oxford Translation*, 6. print., with. corr. Bollingen Series (General) ; 192. Princeton, NJ: Princeton University Press, 2014.

Atkins, P. W., (Peter William). *The Laws of Thermodynamics : A Very Short Introduction*. Very Short Introductions. Oxford: Oxford University Press, 2010.

Bowie, Andrew. "Friedrich Wilhelm Joseph von Schelling." In *The Stanford Encyclopedia of Philosophy*, Spring 2023, edited by Edward N. Zalta and Uri Nodelman. Metaphysics Research Lab, Stanford University, 2023. Accessed February 26, 2024. https://plato.stanford.edu/archives/spr2023/entries/schelling/.

Brading, Katherine, Elena Castellani, and Nicholas Teh. "Symmetry and Symmetry Breaking." In *The Stanford Encyclopedia of Philosophy*, Fall 2023, edited by Edward N. Zalta and Uri Nodelman. Metaphysics Research Lab, Stanford University, 2023. Accessed January 27, 2024. https://plato.stanford.edu/archives/fall2023/entries/symmetry-breaking/.

Brewing, Pasteur. "Louis Pasteur and the History of Spontaneous Generation." Pasteur Brewing, October 1, 2011, 11:17 p.m. (Z). Accessed February 21, 2024. https://www.pasteurbrewing.com/louis-pasteur-and-the-history-of-spontaneous-generation/.

Burch, Robert, and Kelly A. Parker. "Charles Sanders Peirce." In *The Stanford Encyclopedia of Philosophy*, Spring 2024, edited by Edward N. Zalta and Uri Nodelman. Metaphysics Research Lab, Stanford University, 2024. Accessed January 21, 2024. https://plato.stanford.edu/archives/spr2024/entries/peirce/.

Campbell, Joseph Keim. "Descartes on Spontaneity, Indifference, and Alternatives." In *New Essays on the Rationalists*, edited by Rocco J. Gennaro and Charles Huenemann, 179–199. Oxford University Press, February 1, 2003.

Driessen, Alfred. "Aristotle and the Foundation of Quantum Mechanics." *Acta Philosophica* 29, no. II (2020): 395–414.

Dyck, Corey W. “Spontaneity before the Critical Turn: The Spontaneity of the Mind in Crusius, the Pre-Critical Kant, and Tetens.” *Journal of the History of Philosophy* 54, no. 4 (2016): 625–648.

Eagle, Antony. “Chance versus Randomness.” In *The Stanford Encyclopedia of Philosophy*, Spring 2021, edited by Edward N. Zalta. Metaphysics Research Lab, Stanford University, 2021. Accessed February 3, 2024. https://plato.stanford.edu/archives/spr2021/entries/chance-randomness/.

Earman, John. “Curie’s Principle and Spontaneous Symmetry Breaking.” *International Studies in the Philosophy of Science* 18, nos. 2-3 (July 1, 2004): 173–198.

———. “Determinism: What We Have Learned and What We Still Don’t Know.” In *Freedom and Determinism*, edited by Joseph K. Campbell, 21–46. Bradford Book/Mit Press, 2004.

Faye, Jan. “Copenhagen Interpretation of Quantum Mechanics.” In *The Stanford Encyclopedia of Philosophy*, Summer 2024, edited by Edward N. Zalta and Uri Nodelman. Metaphysics Research Lab, Stanford University, 2024. Accessed May 3, 2024. https://plato.stanford.edu/archives/sum2024/entries/qm-copenhagen/.

Fisch, Max H. “Peirce’s Arisbe: The Greek Influence in His Later Philosophy.” *Transactions of the Charles S. Peirce Society* 7, no. 4 (1971): 187–210.

Frisch, Mathias. “Causation in Physics.” In *The Stanford Encyclopedia of Philosophy*, Winter 2023, edited by Edward N. Zalta and Uri Nodelman. Metaphysics Research Lab, Stanford University, 2023. Accessed May 11, 2024. https://plato.stanford.edu/archives/win2023/entries/causation-physics/.

Gaudenzi, Rocco. *Historical Roots of Spontaneous Symmetry Breaking: Steps Towards an Analogy*. SpringerBriefs in History of Science and Technology. Cham: Springer International Publishing, 2022.

Ghirardi, Giancarlo, and Angelo Bassi. “Collapse Theories.” In *The Stanford Encyclopedia of Philosophy*, Summer 2020, edited by Edward N. Zalta. Metaphysics Research Lab, Stanford University, 2020. Accessed January 27, 2024. https://plato.stanford.edu/archives/sum2020/entries/qm-collapse/.

Hansen, Chad. “Daoism.” In *The Stanford Encyclopedia of Philosophy*, Spring 2020, edited by Edward N. Zalta. Metaphysics Research Lab, Stanford University, 2020. Accessed March 6, 2024. https://plato.stanford.edu/archives/spr2020/entries/daoism/.

Hartshorne, Charles. “Charles Peirce and Quantum Mechanics.” *Transactions of the Charles S. Peirce Society* 9, no. 4 (1973): 191–201.

Heelan, Patrick A. *Quantum Mechanics and Objectivity*. Dordrecht: Springer Netherlands, 1965.

Heisenberg, Werner, and F. S. C. Northrop. *Physics and Philosophy : The Revolution in Modern Science*. First Harper Torchbook edition. Edited by Ruth Nanda Anshen. World Perspectives; v. 19. New York: Harper & Row, 1962.

Hobbs, Charlie. “Peirce’s Tychism and the Epicurean Swerve.” *Southwest Philosophical Studies* 30 (2008). https://www.academia.edu/598694/Peirces_Tychism_and_the_Epicurean_Swerve.

Hoefer, Carl. “Causal Determinism.” In *The Stanford Encyclopedia of Philosophy*, Winter 2023, edited by Edward N. Zalta and Uri Nodelman. Metaphysics Research Lab, Stanford University, 2023. Accessed February 3, 2024. https://plato.stanford.edu/archives/win2023/entries/determinism-causal/.

Jaeger, Gregg. “Quantum Potentiality Revisited.” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 375, no. 2106 (October 2, 2017): 20160390.

Johnson, Monte Ransome. “Nature, Spontaneity, and Voluntary Action in Lucretius.” In *Lucretius: Poetry, Philosophy, Science*, edited by Daryn Lehoux, A. D. Morrison, and Alison Sharrock, 98–130. Oxford University Press, May 16, 2013.

Jorati, Julia. *Leibniz on Causation and Agency*. Cambridge: Cambridge University Press, 2017.

———. “Three Types of Spontaneity and Teleology in Leibniz.” *Journal of the History of Philosophy* 53, no. 4 (2015): 669–698.

Klein, Martin J., A.J. Kox, and Robert Schulman, eds. *Collected Papers of Albert Einstein, Vol. 6: The Berlin Years / Writings 1914-1917*. Vol. 6. Collected Papers of Albert Einstein. Princeton University Press, 1996.

Konstan, David. “Epicurus,” January 10, 2005. Accessed April 20, 2024. https://plato.stanford.edu/ENTRIES/epicurus/.

Kožnjak, Boris. “Aristotle and Quantum Mechanics: Potentiality and Actuality, Spontaneous Events and Final Causes.” *Journal for General Philosophy of Science* 51, no. 3 (September 1, 2020): 459–480.

Kress, Emily. “Aristotle on Spontaneous Generation, Spontaneity, and Natural Processes.” In *Oxford Studies in Ancient Philosophy, Volume 58*, edited by Victor Caston. Oxford University Press, November 17, 2020.

Landsman, Klaas. “Bohmian Mechanics Is Not Deterministic.” *Foundations of Physics* 52, no. 4 (2022): 1–17.

———. *Foundations of Quantum Theory*. Vol. 188. Fundamental Theories of Physics. Cham: Springer International Publishing, 2017.

———. “Randomness? What Randomness?” *Foundations of Physics* 50, no. 2 (February 1, 2020): 61–104.

———. “Typical = Random.” *Axioms* 12, no. 8 (8 2023): 727.

Leibniz, Gottfried Wilhelm, and Samuel Clarke. *Leibniz and Clarke: Correspondence*. Edited by Roger Ariew. Indianapolis: Hackett Publishing Company, 2000.

Lewis, Peter J. “Collapse Theories,” November 6, 2017. Preprint.

Lucretius. *De Natuur van de Dingen*. Translated by Piet Schrijvers. Groningen: Historische Uitgeverij, 2008.

Lucretius Carus, Titus, W. H. D. Rouse, and Martin Ferguson Smith. *On the Nature of Things*. New edition. 1 online resource vols. Cambridge, MA: Harvard University Press Cambridge, MA, 1924.

Lüthy, Christoph H., and Carla Rita Palmerino. "Conceptual and Historical Reflections on Chance (and Related Concepts)." In *The Challenge of Chance: A Multidisciplinary Approach from Science and the Humanities*, edited by Klaas Landsman and Ellen van Wolde, 9–47. The Frontiers Collection. Cham: Springer International Publishing, 2016.

Mayorga, Rosa. "Scientific Pride and Metaphysical Prejudice: Ens Quantum Ens, Quantum Theory, and Peirce." In *The Oxford Handbook of Charles S. Peirce*, edited by Cornelis de Waal, 0. Oxford University Press, February 19, 2024.

Miller, Willard M. "Aristotle on Necessity, Chance, and Spontaneity." *New Scholasticism* 47, no. 2 (1973): 204–213.

Norton, John D. "Causation as Folk Science." *Philosopher's Imprint* (Ann Arbor, MI) 3, no. 4 (November 1, 2003).

———. "The Dome: An Unexpectedly Simple Failure of Determinism." *Philosophy of Science* 75, no. 5 (2008): 786–798.

"Online Etymology Dictionary." Accessed January 19, 2023. https://www.etymonline.com.

"Oxford Languages and Google - English | Oxford Languages." Accessed February 4, 2024. https://languages.oup.com/google-dictionary-en/.

Panayides, Christos. "Aristotle on Chance and Spontaneous Generation. A Discussion Note." *Filozofia (Philosophy)* 68, no. 2 (2013).

Peirce, C. S. "The Doctrine of Necessity Examined." *The Monist* 2, no. 3 (1892): 321–337.

Reynolds, Andrew. "Peirce's Cosmology and the Laws of Thermodynamics." *Transactions of the Charles S. Peirce Society* 32, no. 3 (1996): 403–423.

———. *Peirce's Scientific Metaphysics: The Philosophy of Chance, Law, and Evolution*. Vanderbilt University Press, 2002.

Ritter, Joachim Friedrich, Karlfried Gründer, Günther Bien, Rudolf Eisler, Margarita Kranz, and Gottfried Gabriel. *Historisches Wörterbuch der Philosophie*. Völlig neubearb. Ausg. Vol. Se-Sp. Darmstadt: Wissenschaftliche Buchgesellschaft ; 1971.

Roman-Alcala, Ramón. "Deviations and Uncertainty: the Concept of Swerve in Epicurus and Lucretius and Quantum Mechanics," 1:225–236. Book 2. International Multidisciplinary Scientific Conference on Social Sciences and Arts-SGEM. Vienna, 2017.

Russell, Paul. "Hume on Free Will." In *The Stanford Encyclopedia of Philosophy*, Fall 2021, edited by Edward N. Zalta. Metaphysics Research Lab, Stanford University, 2021. Accessed February 26, 2024. https://plato.stanford.edu/archives/fall2021/entries/hume-freewill/.

Rutherford, Donald. "Leibniz on Spontaneity." In *Leibniz: Nature and Freedom*, edited by Donald Rutherford and J. A. Cover. Oxford University Press, January 4, 2005.

Rynasiewicz, Robert. "Newton's Views on Space, Time, and Motion." In *The Stanford Encyclopedia of Philosophy*, Spring 2022, edited by Edward N. Zalta. Metaphysics Research Lab, Stanford University, 2022. Accessed May 28, 2024. https://plato.stanford.edu/archives/spr2022/entries/newton-stm/.

Sgarbi, Marco. *Kant on Spontaneity*. Continuum Studies in Philosophy. London ; Continuum, 2012.

Straumann, Norbert. "Einstein in 1916: "On the Quantum Theory of Radiation"," March 23, 2017. arXiv: 1703.08176.

Strien, Marij van. "The Norton Dome and the Nineteenth Century Foundations of Determinism." *Journal for General Philosophy of Science / Zeitschrift für Allgemeine Wissenschaftstheorie* 45, no. 1 (2014): 167–185.

Strocchi, Franco. "Spontaneous Symmetry Breaking in Classical Systems." *Scholarpedia* 6, no. 10 (October 7, 2011): 11195. Accessed January 27, 2024. http://www.scholarpedia.org/article/Spontaneous_symmetry_breaking_in_classical_systems.

Terekhovich, Vladislav. "Metaphysics of the Principle of Least Action." *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 62 (May 1, 2018): 189–201.

"The First Quantum Cosmologist – Sean Carroll," August 21, 2008. Accessed April 16, 2024. https://www.preposterousuniverse.com/blog/2008/08/21/the-first-quantum-cosmologist/.

Trépanier, Simon. "Lucretius." In *The Stanford Encyclopedia of Philosophy*, Winter 2023, edited by Edward N. Zalta and Uri Nodelman. Metaphysics Research Lab, Stanford University, 2023. Accessed January 20, 2024. https://plato.stanford.edu/archives/win2023/entries/lucretius/.

V1adis1av. *English: A Diagram of Stimulated Emission.* May 3, 2008. https://commons.wikimedia.org/wiki/File:Stimulated_Emission.svg.

Vavilov, S. I. "Lucretius' Physics." *Philosophy and Phenomenological Research* 9, no. 1 (1948): 21–40.