Time in Classical Physics

Forthcoming in *The Routledge Companion to Philosophy of Time* (ed. Nina Emery)

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September 17, 2025

Abstract

Time plays an ambiguous role in classical physics. On the one hand, classical physics allows for a picture of time largely fitting with common-sense views about time, as one-dimensional, and flowing from past to future. On the other, various features of classical physics and formulations of classical mechanics give a less familiar picture of time, as symmetrical between past and future, with apparent teleological qualities. This chapter surveys these varied temporal features of classical physics and draws some conclusions about how to interpret 'classical time'.

0. Introduction

What is 'classical' time? This question can be read in various ways, but in this chapter the focus will be on ways time can and should be understood in classical physics. So the next question is 'what is classical physics?' Ordinarily, when 'classical' is used in contemporary physics, it is shorthand for physics that is neither relativistic nor quantum. This can include classical mechanics — how bodies behave under the influence of forces, as described by the Newtonian laws of motion –, electromagnetism, thermodynamics and statistical mechanics. In this chapter, I will look at the ways in which time can be understood based on the various ways it appears within classical physics, primarily within classical mechanics, and argue that classical time is potentially much more minimal and out-of-keeping with intuitive pictures of time than is often suggested.

1 Absolute, true and mathematical...

The obvious place to start with any discussion of time in classical physics is Newton's remarks about time in his *Philosophiæ Naturalis Principia Mathematica*. There, Newton states the following:

> Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year. (Newton, 1689; trans. Andrew Motte, 1729, rev. Florian Cajori, 1934: 6–12)

This is a definition of time, reflecting what Newton thought needed to be assumed in order to make sense of his laws of motion. In this definition, we are immediately faced with the notion of time as something absolute, flowing, and contrasted by Newton with a second concept of time, 'relative, apparent, and common' time, which corresponds to time as we measure and experience it. Focusing on the former, Newton appears to have the idea that there is a thing, 'absolute, true, and mathematical' time, that exists independently of our ways of constructing, recording and measuring time. We have many different types of clock that we can use to measure the durations of processes, or to compare different intervals of time. But these are all potentially fallible in various ways. For Newton, the 'time' referred to in the laws of motion is that of an independent 'true' time that has the ideal properties he mentions. There is nothing in the Scholium in the way of an argument that this notion of time exists, or that it is something that has measurable effects on the material world (unlike his famous arguments for the reality of absolute space by reference to centrifugal forces, such as the 'Bucket' experiment [see Sklar (1974, 182–184)]. Rather, Newton's absolute time plays a constitutive role insofar as, without true time, the laws of motion could not be properly understood; as Gryb and Thébault (2023, 31) put it, "Newton can be understood as offering a defence of his conception of time as a necessary presupposition for a successful theory of dynamics."

Newtonian time is defined by three features for which Newton provides the relevant contrasting notions: it is 'true' and not 'apparent'; 'absolute' and not 'relative'; 'mathematical' and not 'common'. The true/apparent distinction picks on the difference between time as we experience and interact with it in the world, and time as we conceive of it independently of our experience. We can experience time in different ways, for example, due to the psychology of temporal perception (it runs fast or slow to us depending on what we happen to be doing), the infelicities of time measurement, and the discrepancy between different means of tracking time's passage. But we can form an abstract, ideal conception of time as something universal, ticking away at a continuous, constant pace, independent of our ways of physically interacting with it. The mathematical/common distinction concerns the difference between the mathematically precise ways we can represent time and durations, and the variety of ways in which we interact with temporal things, and think and talk about time in everyday discourse. The absolute/relative distinction is perhaps the most written-about, concerned with whether time has an existence beyond the temporal relations between things. Relative time is something measurable — we can measure the time it takes for Usain Bolt to run 100m by timing his start and finish against a stopwatch, and we can use Earth's motion relative to the Sun to establish the number of years that have passed since your birth. But do either of these devices measure time itself? If there were a background universal 'absolute' time, ticking away behind the scenes, it isn't clear how we could possibly measure such a thing. Ernst Mach was famously unimpressed by Newton's idea of both absolute space and time, referring to them as "monstrous conceptions" and remarking that although Newton "spoke much about these things, [...he] made no serious application of them." (Mach, 1988)

Newton's own view of time was awash with various apparent metaphysical commitments that can and have been queried and rejected by philosophers. But there are certain formal properties of time that are consistent across classical mechanics. Time is one-dimensional, as opposed to the three-dimensionality of space. In other words, whereas in a Cartesian coordinate system we need three numbers to specify an object's location in space, we need only one to specify an event's location in time. The independent metrics of three-dimensional space and one-dimensional time allow us to speak of *moments* of time, and to think of simultaneity as an *equivalence relation.* Simultaneity in classical time is symmetrical (if x is simultaneous with y, then y is simultaneous with x), reflexive (x is simultaneous with itself), and transitive (if x is simultaneous with y, and y is simultaneous with z, then x is simultaneous with z). These three features ensure that classical simultaneity gives us equivalence classes of events — effectively we can define a moment of time in terms of some set of events that are each simultaneous with each other and are not simultaneous with any other event. It is this idea of a one-dimensional, linear series of moments of time that has motivated many to hold that classical physics supports a picture of time largely in line with our common-sense picture of time.

2 Classical time and temporal metaphysics

It is common to see claims like the following: before relativity theory, physical time was largely in line with common sense. One way to understand this is to see that Newton's conception of true mathematical time fits a standard way of thinking about time — it is absolute, and flows independently of our perception. This view fits with that of the 'A-theory' of time, one of the canonical theories in contemporary philosophy of time, alongside the B-theory and (more recently) the C-theory.

A-theories of time are characterised by their view of time as inherently dynamic, divided into distinct regions of 'past', 'present' and 'future', and the present moment moving to later and later times. There are various different kinds of A-theory, all of which are standardly defended as in line with key aspects of our common-sense beliefs about time. For example, Presentism holds that only present things exist, with our world being a three-dimensional entity that simply changes, and the Growing Block theory holding that the past and present both exist, with reality 'growing' as new times come into being through becoming present and then past. On the face of it, such views have much in common with the Newtonian idea of an absolute, flowing time. The A-theory is traditionally contrasted with the B-theory of time, which holds that the flow or dynamism of time is not some additional feature of time over and above the existence of events ordered from earlier to later, which has led to B-theories being referred to as 'static' views of time, or fitting with a 'block universe' conception of time. The 'A' and 'B' in these theories refer back to J.M.E. McTaggart's (1908) terminology of the A-series (the ordering of things in time in terms of their degrees of 'pastness', 'presentness' and 'futurity) and the B-series (the ordering of things in time in terms of relations of 'earlier than' and 'later than'). For completeness, a C-theory of time can be formulated in terms of McTaggart's third series, the 'C-series', which holds that things in time are related by a symmetric relation of 'temporal betweenness', corresponding to the idea of time as ordered but undirected (see Farr (2020) for details).

We can ask whether classical time fits better with an A-theoretic, B-theoretic, or C-theoretic view of time. For instance, is classical time dynamic and composed of moments of past/present/future, like the A-theory? Or should classical time be considered as static, or even directionless, like the B- or C-theories? There is not clearly a fact of the matter here. Rather, the various features of classical time can be taken to motivate a range of different temporal metaphysics, from the richness of the A-theory to the sparseness of the C-theory: on the one hand, classical time is far more amenable to an A-theoretic reading than relativistic time; on the other hand, some specific features of classical time motivate a C-theoretic reading.

3 Classical time and temporal passage

The main features of classical time that fit with the A-theory are those that contrast with relativistic time. It is well-known (see Chapters 30 and 31 in this volume) that the special and general theories of relativity adopt a single metric for spacetime, and do not neatly support the notion of a worldwide 'moment' of time. However, classical time is much more attractive to the A-theorist given the independent metrics of space and time, which allow us to divide the universe into a series of global moments of time. With this basic structure of time, we can denote the moment of time composed of all those events simultaneous with us right now as the 'present' moment of time, with earlier times making up the 'past' and later times making up the 'future'. This shows that classical time is hospitable to the basic structures assumed by the A-theory, for example allowing one to read classical physics as consistent with Presentism or the Growing Block theory. Moreover, the classic Newtonian description of time in the Scholium makes reference to the property of 'flow', the feature of time standardly taken by A-theorists (and also McTaggart himself) to be the essential feature of time that distinguishes it from space. A more general sense in which classical mechanics fits with the A-theory is that it accords to what Smolin (2009) calls the 'Newtonian schema', the idea that the dynamical laws determine how a system's initial state ('initial conditions') evolves over time, giving the picture of a universe that unfolds from an initial moment to later times. However, the A-theoretic conception of time can also be seen as inconsistent with some features of classical time.

First, the notion of the 'flow' or 'passage' of time is notoriously ambiguous. Although the A-theory takes this as a special, unique feature of time, akin to the flow of a river, it is also widely used in a more metaphorical sense, not literally pointing to a special property of time. There is both disagreement as to whether Newton himself was ever committed to a literal sense of time as flowing, and wider philosophical criticism concerning whether flowing time itself is tenable within classical physics. It's been widely suggested that the term is merely metaphorical, reflecting a standard way of talking about temporal duration — for example, Earman (1989) refers to this attitude when remarking that "[w]hen Newton says that absolute time "flows equably", he is not to be parsed as saying that time flows and that it flows equably." Against this reading, Arthur (1995) has suggested that a wider appreciation of Newton's notion of fluxions, as in his discussion of calculus, supports the reading of Newton as committed to the idea that time really does flow: "Newton's time flows because all physical quantities (fluents) are continuously generated in it, each having its own fluxion at any instant" (350). Earman's own thought here is guided by a long-standing philosophical criticism of flowing time as presupposing a second-order time relative to which it flows (and, some have argued, so on ad infinitum), holding that "a literal notion of flow would presuppose a substratum with respect to which the flow takes place." Variations of this argument have also been made by Broad (1938, 277–279) and Smart (1949, 484). The idea is that classical physics, in lacking any such two-dimensional conception of time, lacks the resources to describe time as literally flowing. Similar criticisms have been posed against the intelligibility of time flow by questions such as 'how fast does time flow', which Smart suggests either has no answer, or once more brings in the need for extra time dimensions.

Second, there are various symmetries of classical physics that can lend support to the rival theories of time. The classical equations of motion are time translation invariant, meaning that the choice of the temporal origin of some coordinate system (time t_0) is arbitrary. This symmetry reflects the fact that classical physics is insensitive to the time at which an experiment is conducted — an experiment at time t_0 should have the same result as an identical experiment in identical conditions at any other time. One way to read the time translation invariance of the classical laws of physics is that the world contains no 'privileged' moment of time, insofar as each moment of time is qualitatively identical to any other moment; e.g. there is no intrinsic physical property that one moment of time has that other moments lack, implying that 'presentness' (or 'pastness' or 'futurity') are not 'physical' properties. In response, the A-theorist can deny that this kind of symmetry of the laws of physics in any way prohibits the present moment from being metaphysically privileged; so long as classical time gives us the basic structure needed to attach an A-theoretic metaphysics of time, then it 'supports' it in this basic sense.

4 Classical time and time direction

Alternatively, we could adopt a minimalist approach to ontology, and commit only to the minimal ontological structure needed to support the accepted scientific theories. On this approach, it can be argued that classical physics does not commit us to anything beyond the temporal structure of the C-theory. Not only is classical time consistent with a static conception of time, but it also offers specific motivations for thinking of time as directionless. It is widely accepted that classical mechanics is 'time symmetric' or 'time reversal invariant'. One way to understand this is that the classical equations of motion are of a form that, for any solution to those equations, its 'time reverse' is also a solution to them. In other words, if some process is allowed by the laws of classical physics in one direction of time, it's also allowed in the other direction of time. Take for instance a ball of mass m rolling at velocity v from left to right from your perspective. Take the 'start' point of the motion as being position x_0 at time t_0 and the end point being position x_1 at time t_1. The reverse process is then a ball with mass m rolling from x_1 to x_0 in the same amount of time. In this case, since it's rolling at the same speed but in the opposite direction, its velocity is reversed, to $-v$. For simplicity, denote the 'reverse' process as also running from t_0 to t_1. In that case, if our theory is time reversal invariant, it holds that if the process (x_0, t_0) to (x_1, t_1) is allowed by the laws of motion, then so is the process (x_1, t_0) to (x_0, t_1). In practice, time reversal symmetry for most classical theories involves the application of a non-trivial 'time reversal operator' to states in order to ensure that a sequence of states in reverse temporal order obeys the relevant laws (see Roberts (2021) for a recent overview).

Modulo various assumptions about what time reversal actually reverses (such as velocity, but also related quantities like momentum, and less-obviously-related things like magnetic fields — see Albert (2000, ch. 1)), the theories that comprise classical physics are time reversal invariant, meaning that the world described by classical physics is time reversal invariant. So, does this mean that time is 'symmetrical' according to classical physics? No. At least, it doesn't follow directly. Firstly, what does it mean for time to be symmetric? Symmetry is ordinarily understood as a relation between things; time could be 'symmetric' insofar as the earlier-to-later direction is shares some particular relevant property with to the later-to-earlier direction. Clearly our universe is not straightforwardly symmetrical in time, since the two directions in time *look* very different in various key ways. For one thing, the past-to-future and future-to-past directions are not mirror images, since that would require only exactly symmetrical processes occur, presumably centred on the present time as the origin of that symmetry. More generally, we also know that all sorts of types of process tend to occur only towards the future and not towards the past (e.g. glasses tend to smash towards the future and un-smash towards the past — see Chapter 32 in this volume). More importantly, the time reversal invariance of a theory does not entail that in worlds described by that theory, anything that can happen forwards in time can also happen backwards in time. Maudlin (2007, 119) argues that time reversal invariance merely tells us that "if states T0, T1, T2, ... TN are physically allowable as time runs from T0 to TN in some direction, then the sequence TN*, ... T2*, T1*, T0* is also allowed, where the * represents the time reversal operation as applied to the states, and where time runs from TN* to To* in the same direction as it runs from To to TN." His point is that one cannot simply take the apparent time reversal invariance of a theory to entail something about the nature of time, since all that we actually observe when testing such theories is processes that run from earlier to later.

A more sophisticated philosophical argument is required at this point to use the apparent time reversal invariance of classical physics to justify the claim that classical time is undirected. Such arguments exist in various forms. Reichenbach (1956) suggests that the time reversibility of classical physics is evidence that time is undirected on the grounds that, in the context of classical physics "positive and negative time supply equivalent descriptions, and it would be meaningless to ask which of the two descriptions is true" (31-32). A very similar view is defended by Gold (1966, 327), who notes "the description of our universe in [backwards] time sounds very strange but it has no conflict with any laws of physics. [The] strange description is not describing another universe, or how it might be but isn't, but it is describing the very same thing." Both Reichenbach and Gold are giving a specific reading of time reversal here. On their view, two processes that are the time reverse of each other (e.g. two balls of equal mass moving with equal speeds in opposite directions) are, from the perspective of classical physics, the same process differently described. The underlying reasoning here is that because any process allowable by classical physics can occur in either direction in time, the direction of time itself is superfluous. This is sometimes referred to as a 'passive' interpretation of time reversal (see Earman (1974); Farr (2020)).

The passive reading of time reversal is not forced upon us. Some, like Maudlin (2007) and Earman (1974), have criticised the view. For instance, the passive view has some prima facie inconsistency with standard textbook classical physics. Within classical mechanics, systems are described in terms of their instantaneous state — for instance, the positions and momenta of their constituent parts for each spatial dimension — and the dynamical laws describe how this instantaneous state changes over time due to the input of forces such as gravity. This very notion of an instantaneous state is itself beset by interpretative worries, such as what it means for an object to have a velocity at a single instant of time (see Albert (2000); Arntzenius (2000, 2003); Lange (2005); McCoy (2018); Smith (2003)). But a more pressing issue in the context of the direction of time is that instantaneous states include quantities that appear to imply a fact about the direction of time, such as momentum (in Hamiltonian mechanics) and velocity (in Lagrangian mechanics), and related quantities such as the magnetic field in classical electromagnetism (see Albert (2000); Earman (2002); Malament (2004); Arntzenius and Greaves (2009) for a discussion of this case). To use the simplest example for illustration, if a particle at time t has some non-zero velocity v, this appears to tell us the direction the time. Why? Because the particle only appears to have that velocity relative to a direction of time. If we were to view the particle in reverse time, the particle would appear to have velocity $-v$, because it would look like it's moving in the opposite direction. So the choice of direction of time determines the instantaneous velocity we assign the particle. This is why the time reversal operator typically has to transform parts of the instantaneous state of a system. Maudlin (2007, 119) remarks on this point that "it suggests that even for an instantaneous state, there is a fact about *how it is oriented with respect to the direction of time*." Alternatively we could accept the weaker claim that our conventional means of representing states of the world in classical mechanics involves an assumption about the direction of time, but this doesn't mean that the world is represented by classical mechanics as directed in time.

A related feature of classical mechanics that has been used to motivate directionless time is its two-way determinism of states: given some specified state of a system, the relevant dynamical equations are bi-deterministic in that they determine the future and past of the system in equal measure. Bertrand Russell (1913, 15) made reference to this property of the classical laws of physics using the example of the classical law of gravitation, which "makes no difference between past and future the future 'determines' the past in exactly the same sense in which the past 'determines' the future." This feature of classical physics is used by Russell to argue that the language of cause and effect is redundant in physics, since physics suggests that it is no more the case that later things are produced by earlier things than vice versa; instead the laws of classical physics describe functional relationships between states of the world at different times that are symmetrical with respect to the past-to-future and future-to-past directions. This is in contrast to the more common framing of classical physics in terms of the Newtonian schema, the idea that the laws of physics describe the production later moments of time from some initial conditions. Although the Newtonian schema is popular, it is not the only way to understand the temporal and causal structure of classical physics.

5 Time, causality, and teleology

Wigner (1995, 334) describes how Newton's "most important" achievement was the division of the world into "Initial Conditions and Laws of Nature", noting that "[b]efore Newton there was no sharp separation between the two concepts. [...] After Newton's time the sharp separation of initial conditions and laws of nature was taken for granted and rarely even mentioned." This is the central feature of the Newtonian schema. Certainly, the picture of the world as determined by initial conditions, and then run forwards by the relevant laws of nature is very intuitive, widespread, and influential, and it is easy to see that this picture of nature accords with the A-theory of time. But classical mechanics does not force this particular view of either the laws of nature or causality. As Russell suggested, the classical laws themselves (in his case, gravity) lack the kind of 'causal' asymmetry between earlier and later states, and so also between 'initial' and 'final' states in the Newtonian picture. The mathematical form of the differential equations is such that they express a symmetrical functional relationship between the states of a system at different times. We can think of this general point in the framework of the famous Laplacian Demon. Laplace sought to show the radical determinism of classical mechanics by means of a hypothetical figure who could have knowledge of the precise mechanical state of the world, knowledge of the precise laws of nature, and the computational ability to predict the state of the world at all other times. Laplace's demon would be able not only to predict the future, but also retrodict the past, owing to the two-way nature of the dynamical laws in describing the functional relationships between the world at different times.

This is not to say that the Newtonian schema is untenable. The idea of the world as 'starting out' in some initial state and 'evolving to' later states in a causal-like way is certainly compatible with classical physics, and may very well be the simplest or most useful schema. But it is not the only way to understand classical physics. Joseph-Louis Lagrange introduced a formulation of classical mechanics based on his Principle of Least Action, which is commonly known as Lagrangian mechanics. Lagrangian mechanics gives us what Wharton (2015) calls the 'Lagrangian Schema', an alternative to the Newtonian Schema in which one uses a "two-way map between physical events and mathematical parameters, partially constrains those parameters on some spacetime boundary at both the beginning and the end, and then uses a global rule to find the values of the unconstrained parameters" (p. 182). Wharton notes that a standard attitude towards the Lagrangian schema (an attitude that he rallies against) is that it is mathematically useful but doesn't correspond to the temporal/causal structure of the world: "it may be beautiful, it may be powerful, but it's not how our universe really works" (p. 182). Although Lagrangian mechanics is widely regarded as equivalent to alternative construals of classical mechanics (at least, 'mathematically' or 'formally' equivalent), it differs from the Newtonian schema philosophically due to its apparent teleological qualities. Whereas Newtonian mechanics is ordinary understood as a forwards-only causal view of time evolution of systems, Lagrangian mechanics involves the calculation of the least action, which Max Planck (1949) considered a particularly radical species of causality:

> The least-action principle introduces a completely new idea into the concept of causality: The *causa efficiens*, which operates from the present into the future and makes future situations appear as determined by earlier ones, is joined by the *causa finalis* for which, inversely, the future—namely, a definite goal—serves as the premise from which there can be deduced the development of the processes which lead to this goal. (Planck, 1949, 179–80)

This general way of explaining evolutions via the use of variational principles has been deemed as philosophically problematic due to the difficulty in making sense the apparently teleological nature of such principles. For instance, Fermat's principle, which holds that the path that is taken by a ray between two points is that which can be travelled in the least time, was regarded as philosophically problematic by Feynman on these grounds:

> [Fermat's principle] is a completely different philosophical principle about the way nature works. Instead of saying it is a causal thing, that

> when we do one thing, some thing else happens, and so on, it says this: we set up the situation, and light decides which is the shortest time, or the extreme one, and chooses that path. But what does it do, how does it find out? Does it smell the nearby paths, and check them against each other? (Feynman et al., 1963, 26–27)

This reflects the intuitiveness of the Newtonian schema and counterintuitiveness of the Lagrangian schema. Ben-Menahem (2018) notes that the Principle of Least Action not only lacks the "intuitive causal model" of the world given by the Newtonian schema, but "could easily be construed as reintroducing the teleological language that Newton's system had eschewed," bringing back philosophical views predating modern science. However, Ben Menahem argues that "the appearance of teleology was dispelled" due to the formal equivalence of Newtonian and Lagrangian mechanics. However, this leaves an open problem: what should we make of the fact that, at least at face value, classical mechanics can be construed in such different temporal and causal backdrops?

The fact that the Lagrangian schema is tenable at least suggests that its apparent teleological commitments ought to be better understood and appreciated. Adlam (2018) is suggestive of this approach. Adlam deems the Lagrangian schema as 'temporally non-local' as opposed to the temporal locality of the Newtonian schema. The difference is that whereas time evolution on the Newtonian schema is naturally understood as a 'moment-by-moment' causal process, the Lagrangian schema gives an understanding of time evolution as determined by the action, which is "a property of an entire history rather than a feature of moment-by-moment temporal evolution." Reflecting on the formal equivalence of the two schemas, the fact that the Lagrangian schema has been widely treated as "a mere mathematical tool," while the Newtonian schema is conversely "treated as an approximate description of reality," reflects an what Adlam deems an unjustified asymmetry in treatment of the two view, reflecting a general prejudice for temporal locality. Indeed, since the formal equivalence between the two schemas goes both ways, it's not immediately clear why we should take the Newtonian schema as the default way to understand classical time. Alternatively, one might hold that since the two schemas are equivalent, there is simply no fact of the matter as to which better captures classical time — indeed this was the view ultimately taken by Planck, remarking that "so long as we confine ourselves to the realm of physics, these alternative points of view are merely different mathematical expressions for one and the same fact" (Planck, 1949, 180).

6 Concluding remarks

There is no straightforward answer to the question of what classical mechanics says about the temporal structure of the world. Indeed, there is good reason to think there is no right answer to the question. What is important however is that both the Newtonian and Lagrangian schemas are viable. Moreover, even the Newtonian schema needs to take on board the reversibility and bidirectionality of the central dynamical laws describing motion. Even though it is common to think of classical time as directed and flowing, and generally fitting with common-sense time, there is also plenty of scope for understanding classical time as something symmetrical and undirected, and much more alien to our ordinary conceptions of time. As such, classical physics has a significant neutrality with respect to the nature of time.

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Recommended Reading

Gryb, S., & Thébault, K. (2023) *Time Regained: Volume 1: Symmetry and Evolution in Classical Mechanics* (Oxford University Press) is an excellent recent analysis of a wide range of key questions about the role of time in classical mechanics. Barbour, J. B. (2001) *The discovery of dynamics: A study from a Machian point of view of the discovery and the structure of dynamical theories* (Oxford University Press) offers a historical survey of issues about the role of time in classical mechanics, defending the 'Machian' relationist view of time. And Maudlin, T. (2012) *Philosophy of Physics: Space and Time* (Princeton University Press) gives an engaging and nuanced take on the construction of time from early classical physics to relativistic physics. For the various philosophical questions that arose surrounding the concept of absolute time around the time of Newton, see Emily Thomas' excellent book Thomas, E. (2018) *Absolute time: Rifts in early modern British metaphysics* (Oxford University Press). For Newton's own view of time, Cohen, I. B., & Smith, G. E. (Eds.) (2002) *The Cambridge Companion to Newton* (Cambridge University Press) offers a wide range of essays covering key topics; see especially Robert DiSalle's chapter 'Newton's philosophical analysis of space and time' (Ch. 1); see also the Schliesser, E. (2013) 'Newton's philosophy of time' in *A Companion to the Philosophy of Time* (Dyke, H., & Bardon, A. Eds, Wiley-Blackwell, pp. 87-101) and Brading, K. (2016) 'Time for empiricist metaphysics', in *Metaphysics and the Philosophy of Science: New Essays* (Oxford University Press) for a discussion of Newton's notion of true and mathematical time. For further discussion of the issue of teleology in Lagrangian mechanics, see chapter 6 of Ben-Menahem, Y. (2018) *Causation in science*, Princeton University Press, and Glick, D. (2023) "The principle of least action and teleological explanation in physics," *Synthese*, 202(1), 25.