

IPP-SR-1: Newton's laws of motion

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HT24

The course

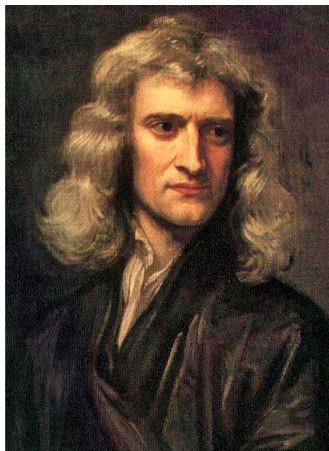
1. Newton's laws
2. Galilean invariance
3. The Michelson-Morley experiment
4. Einstein's 1905 derivation of the Lorentz transformations
5. Spacetime structure
6. General covariance
7. Relativity and conventionality of simultaneity
8. Frame-dependent effects
9. The twin paradox
10. Dynamical and geometrical approaches to relativity
11. Presentism and relativity
12. Acceleration and redshift

Books

- ▶ Harvey R. Brown, *Physical Relativity: Spacetime Structure from a Dynamical Perspective*, Oxford: Oxford University Press, 2005.
- ▶ Tim Maudlin, *Philosophy of Physics Volume I: Space and Time*, Princeton: Princeton University Press, 2012.
- ▶ James Read, *Special Relativity*, Cambridge: Cambridge University Press, 2023.

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- ▶ James Read, *Special Relativity*, Cambridge: Cambridge University Press, 2023.
- ▶ Hans Reichenbach, *The Philosophy of Space and Time*, New York: Dover, 1957.
- ▶ Roberto Torretti, *Relativity and Geometry*, New York: Dover, 1996.
- ▶ Michael Friedman, *Foundations of Space-Time Theories*, Princeton: Princeton University Press, 1983.



(1642-1726/27)

Today

Newton's laws

Inertial frames

Force-free particles

Newton's third law

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Newton's laws of motion

- N1L: Force-free particles travel with uniform velocity.
- N2L: The total force on a body is equal to the product of that body's mass and its acceleration. ($\mathbf{F} = m\mathbf{a}$.)
- N3L: Action and reaction are equal in magnitude and opposite in direction—i.e., if one body exerts a force \mathbf{F} on a second body, then the second exerts a force $-\mathbf{F}$ on the first.

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5. In which frames of reference are these laws supposed to hold?

A logician's nightmare...

It [Newton's first law] reads in detailed formulation necessarily as follows: Matter points that are sufficiently separated from each other move uniformly in a straight line—provided that the motion is related to a suitably moving coordinate system and that the time is suitably defined. Who does not feel the painfulness of such a formulation? But omitting the postscript would imply a dishonesty. (Einstein, 1920)

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The first law ... is a logician's nightmare. ... To teach Newton's laws so that we prompt no questions of substance is to be unfaithful to the discipline itself. (Rigden, 1987)

Hertz on the foundations of mechanics

It is quite difficult to present the introduction to mechanics to an intelligent audience without some embarrassment, without the feeling that one should apologize here and there, without the wish to pass quickly over the beginnings. (Hertz, 1894)

Two giants



On exegesis

Note that we're not doing Newton exegesis here—though for some penetrating discussions on how Newton's own views align with these contemporary positions, see (Pooley 2015, ch. 2).

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- ▶ N1L holds only in a certain class of frames of reference—the so-called *inertial frames*.
- ▶ Our first task, then, should be to get clear on what the inertial frames *are*.

Newton's first law

- In a given coordinate system x^μ ($\mu = 0, \dots, 3$), suppose that the path of any free particle can be expressed as

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- ▶ *This* is the property which N1L tells us holds of force-free particles: so in inertial frames, we should have $\frac{d^2 x^\mu}{d\tau^2} = 0$.

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- ▶ So force-free particles *accelerate* in arbitrary frames—they only move on straight lines in the inertial frames.

Definition of inertial frames

In Newtonian theories, and in special relativity, inertial frames have at least the following three features:

- 1. Inertial frames are frames with respect to which force free bodies move with constant velocities.*
- 2. The laws of physics take the same form (a particularly simple one) in all inertial frames.*
- 3. All bodies and physical laws pick out the same equivalence class of inertial frames (universality).*

(Knox 2013, p. 348)

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1. Brown: **yes**.

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2. Friedman: **no**.

Newtonian physics is (would be) true even if there are (were) no inertial frames. The First Law deals with the existence of inertial frames only counterfactually: if there were inertial frames (for example, if there were no gravitational forces), free particles would satisfy $[\frac{d^2 x^\mu}{d\tau^2} = 0]$ in them. (Friedman 1983, p. 118)

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- ▶ **Question:** What do you make of this response?

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In any case, there's still more work for us to do, because we haven't yet defined 'force-free'...

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Force-freeness

To get a better handle on what it means to be ‘force-free’, we must turn first to N2L.

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It will be recalled that the acceleration $\ddot{\mathbf{x}}$ of the body is defined relative to the inertial frame arising out of the first law of motion. It is for this reason that the first law is not a special case of the second for $\mathbf{F} = 0$. (Brown 2005, p. 37, fn. 9)

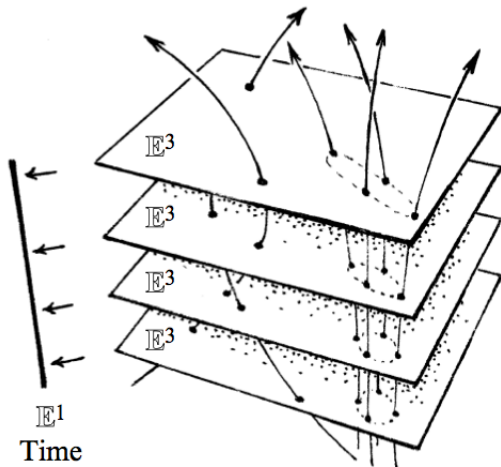
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Let us consider the difference between Friedman and Brown on this issue in more detail.

(Neo-)Newtonian spacetime



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- ▶ A particle is force-free just in case it does not follow a curved path with respect to that standard of straightness.
- ▶ This gives us a *definition* of force-freeness, *and* makes clear that N1L is just a special case of N2L.

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- ▶ Let's think about one contemporary proposal for how this could be realised.
- ▶ (What I'm going to talk about here isn't something *explicitly* proposed by Brown; it's closer to what Huggett (2006) calls 'regularity relationalism'. But there are close connections between these authors: see (Stevens 2020).)

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- ▶ Any particle which does *not* follow a straight-line trajectory in these frames is subject to a genuine force.
- ▶ N1L is not a special case of N2L, because the accelerations in the latter are with respect to the internal structure picked out in the former.
- ▶ Extra forces in non-inertial frames are to be classified as 'fictitious'.

Brown versus Friedman

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- ▶ **Question:** Which account is to be preferred? Why?

Brown on the geometrical approach

What is geometry doing here—codifying the behaviour of free bodies in elegant mathematical language or actually explaining it?

... In what sense then is the postulation of the absolute space-time structure doing more explanatory work than Molière's famous dormative virtue in opium?

(Brown 2005, pp. 23-24)

DiSalle as Brown's ally

When we say that a free particle follows, while a particle experiencing a force deviates from, a geodesic of spacetime, we are not explaining the cause of the difference between two states or explaining 'relative to what' such a difference holds. Instead, we are giving the physical definition of a spacetime geodesic. To say that spacetime has the affine structure thus defined is not to postulate some hidden entity to explain the appearances, but rather to say that empirical facts support a system of physical laws that incorporates such a definition. (DiSalle 1995, p. 327)

More kindred spirits

Note that we do not presuppose the existence of a spacetime structure ... that defines what it is for a motion to be geodesic, but, rather, the other way round: we define geodesic motion as a particularly simple pattern in the entire history of relational change. (Vassallo & Esfeld 2016, p. 106)

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What is the conceptual relation between N3L and N1L and N2L?

Torretti on the third law

[T]he Third Law of Motion furnishes a Newtonian physicist with all he needs for distinguishing, in principle, between a particle acted on by a true force of nature and a free particle accelerating in a particular—necessarily non-inertial—frame. If a material particle α of mass m experiences acceleration \mathbf{a} in an inertial frame F , it will instantaneously react with force $-m\mathbf{a}$ on the material source of its acceleration. There must exist therefore a material system β , of mass m/k , whose centre of mass experiences in F the acceleration $-\mathbf{ka}$. On the other hand, if a particle α accelerates in a non-inertial frame, its acceleration must include a component that is not matched by the acceleration of another material system, in direction opposite to the said component, caused by the action of α on that system. (Torretti 1980, pp. 19-20)

Torretti on the third law

Torretti continues in an endnote:

The criterion furnished by the Third Law does not, of course, amount to an “operational definition” of a freely moving particle and an inertial frame. In the above example, the acceleration of β by α 's reaction will generally be only a component of β 's total acceleration and it might not be easy to discern it. But the criterion surely bestows a definite, intelligible meaning on the italicised expressions. (Torretti 1980, p. 287, n. 16)

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- ▶ The second part of the above quote from Torretti is saying that ' $\neg N1L \rightarrow \neg N3L$ ', i.e. ' $N3L \rightarrow N1L$ '.
 - ▶ But there seem to be counterexamples to this within the context of Newtonian mechanics, as we will discuss below.
- ▶ Torretti is also saying that $N3L$ affords us an (in principle) means of gaining empirical (“operational”) access to the inertial frames.

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- ▶ This frame is non-inertial, but N3L is satisfied.
- ▶ Thus, any claim that the satisfaction of N3L implies that the system in question is being described in an inertial frame of reference is incorrect; rather, the inertial systems are (at best) a *subclass* of the N3L-satisfying systems.

Conclusions on Torretti

So it seems that, *pace* Torretti, satisfaction of N3L does not imply that one is in an inertial frame of reference.

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- ▶ These two approaches will continue to surface throughout the course.
- ▶ We have also explored the interplay between N3L and N1L and N2L.









Summary

- ▶ We've witnessed the difference between a 'dynamical' account of Newton's laws (*à la* Brown) and a 'geometrical' account of Newton's laws (*à la* Friedman).
- ▶ These two approaches will continue to surface throughout the course.
- ▶ We have also explored the interplay between N3L and N1L and N2L.
- ▶ Next time: the *symmetries* of Newtonian mechanics (working towards the conceptual crisis which precipitated special relativity).




References I

-  Julian Barbour, *The Discovery of Dynamics*, Oxford: Oxford University Press, 2001.
-  Harvey R. Brown, *Physical Relativity*, Oxford: Oxford University Press, 2005.
-  Robert DiSalle, “Spacetime Theory as Physical Geometry”, *Erkenntnis* 42(3), pp. 317-337, 1995.
-  Robert DiSalle, “Space and Time: Inertial Frames”, in E. N. Zalta (ed.), *The Stanford Encyclopedia of Philosophy*, 2020.
-  John Earman and Michael Friedman, “The Meaning and Status of Newton’s Law of Inertia and the Nature of Gravitational Forces”, *Philosophy of Science* 40(3), pp. 329-359, 1973.
-  Albert Einstein, “Inwiefern läßt sich die moderne Gravitationstheorie ohne die Relativität begründen”, *Naturwissenschaften* 8, pp. 1010-1011, 1920.
-  Michael Friedman, *Foundations of Space-Time Theories*, Princeton, NJ: Princeton University Press, 1983.

References II

-  David J. Griffiths, *Introduction to Electrodynamics*, fourth edition, Boston, MA: Pearson, 2013.
-  Heinrich Hertz, *Die Prinzipien der Mechanik*, Leipzig: J. A. Barth, 1894.
-  Nick Huggett, “The Regularity Account of Relational Spacetime”, *Mind* 115(457), pp. 41-73, 2006.
-  Eleanor Knox, “Effective Spacetime Geometry”, *Studies in History and Philosophy of Modern Physics* 44, pp. 346-356, 2013.
-  Roger Penrose, *The Road to Reality: A Complete Guide to the Laws of the Universe*, London: Jonathan Cape, 2004.
-  Herbert Pfister and Markus King, *Inertia and Gravitation*, Heidelberg: Springer, 2015.
-  Oliver Pooley, *The Reality of Spacetime*, book manuscript, 2015.
-  John S. Rigden, “Editorial: High Thoughts about Newton’s First Law”, *American Journal of Physics* 55, 1987.

References III

-  Syman Stevens, “Regularity Relationalism and the Constructivist Project”, *British Journal for the Philosophy of Science* 71(1), pp. 353-372, 2020.
-  Roberto Torretti, *Relativity and Geometry*, New York, NY: Pergamon, 1983.
-  Antonio Vassallo and Michael Esfeld, “Leibnizian Relationalism for General Relativistic Physics”, *Studies in History and Philosophy of Modern Physics* 55, pp. 101-107, 2016.