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

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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.

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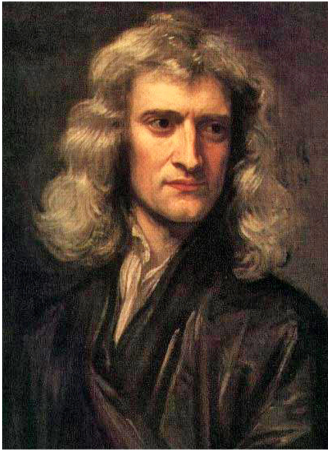
- Hans Reichenbach, *The Philosophy of Space and Time*, New York: Dover, 1957.
- Roberto Torretti, *Relativity and Geometry*, New York: Dover, 1996.
- Michael Friedman, *Foundations of Space-Time Theories*, Princeton: Princeton University Press, 1983.



Today

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Force-free particles

Newton's third law

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Newton's laws of motion

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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...

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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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- 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 ($\mu = 0, \ldots, 3$), 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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$$\frac{d^2 x'^\mu}{d\lambda^2} - \frac{\partial^2 x'^\mu}{\partial x^\rho \partial x^\gamma} \frac{\partial x^\rho}{\partial x'^\nu} \frac{\partial x^\gamma}{\partial x^\sigma} \frac{dx'^\nu}{d\lambda} \frac{dx'^\sigma}{d\lambda} = \frac{d^2 \tau}{d\lambda^2} \frac{d\lambda}{d\tau} \frac{dx'^\mu}{d\lambda}$$

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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 [$\frac{d^2x^\mu}{d\tau^2} = 0$] 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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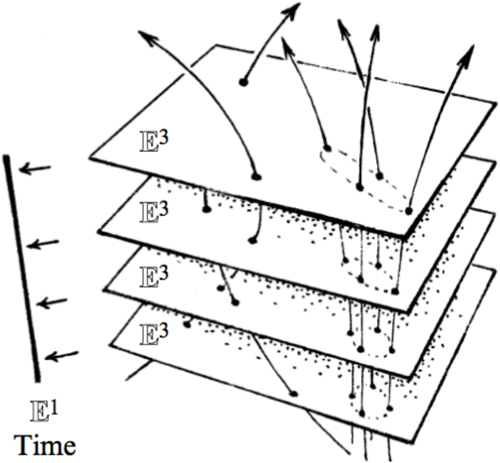
Let us consider the difference between Friedman and Brown on this issue in more detail.

(Neo-)Newtonian spacetime



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- A particle is genuinely accelerating just in case it follows a curved path with respect to the standard of straightness given by that spacetime.
- 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.

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- 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’.

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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)

Immediate questions

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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* **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 $-k\mathbf{a}$. 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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    - Other principles must be invoked to secure the converse direction—e.g. the *relativity principle* (cf. lecture 2).
2. 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.
- Next time: the *symmetries* of Newtonian mechanics (working towards the conceptual crisis which precipitated special relativity).

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