The Principle of Relativity

An Empiricist Analysis

(A relativitás elve – empirista elemzés)
In its standard form, the special principle of relativity is the assertion that “All the laws of physics take the same form in any inertial frame of reference”. This is one of the most fundamental principles of physics; first formulated by Galileo, a fundamental statement in Newton’s mechanics, the basic postulate of Einstein’s special relativity, an indispensable ingredient of the quantum theoretical description of fundamental interactions, providing a prescriptive constraint on the form of physical law for any future theory candidate to respect.

While there is a longstanding discussion about the interpretation of the extended, general principle of relativity, that concerns non-inertial reference frames as well, there seems to be a consensus that the special principle of relativity is absolutely clear and unproblematic. However, once we slow down and take a closer look at the literature on relativistic physics and its philosophy, we face a more confusing picture. There is a huge variety of, sometimes metaphoric, formulations of the relativity principle; there are different, sometimes controversial, views on its actual content; there are inconsistencies in its applications; there are differing understandings of its epistemological status. With a methodology of rigorous conceptual analysis that has become so fruitful in today’s analytic philosophy of science, the aim of this dissertation is to clarify some of these problems.

The first part of the dissertation is concerned with the meaning the relativity principle. We start with a critical examination of Einstein’s 1905 paper on the special theory of relativity that he bases on the postulate of the relativity principle. We identify three different ways in which Einstein applies the principle in the paper; none of which is completely unproblematic in its own terms and, more importantly, none of which is equivalent with one another, some of which are even contradictory together.

Indeed, in trying to understand the precise meaning of the standard, one sentence formulation of the principle, one encounters several obvious questions: What is counted as a “law of physics” here? In what sense can a law of physics be “in” an inertial frame of reference? What does it take to be of the “same form”? etc. To answer these question, we consider an example with respect to which there seems to be an overall consensus in the literature on its being a clear case of the relativity principle. This is the well-known textbook example of the electromagnetic field of a static versus uniformly moving charged particle. Reading off the answers from this case study, following Szabó 2004, we give a preliminary formulation of the relativity principle:

The description of a phenomenon exhibited by a physical system co-moving as a whole with an inertial frame $K$, expressed in terms of the
results of measurements obtainable by means of measuring equipments co-moving with \( K \), takes the same form as the description of the same phenomenon exhibited by the same physical system, except that the system is co-moving with another inertial frame \( K' \), expressed in terms of the measurements with the same equipments when they are co-moving with \( K' \).

In the next step we unpack this verbal formulation in a more formal way. A precise mathematical language is constructed in terms of which the statement of the relativity principle can be formulated as a precise mathematical assertion relating solutions of physical equations (Gömöri and Szabó 2015). The benefit of the formal reconstruction is that it makes explicit all the necessary conceptual components of the relativity principle. The formal language developed is also very much suited to elegantly handle such general scientific concepts as a “law”, or “description” or “physical quantity”. As the most important result of the formalism, the following is proved:

**Result 1** The relativity principle is logically independent from the Lorentz covariance of the physical laws—which is usually taken to be synonymous with the relativity principle.

The basic insight behind the result, easily available in our formalism, is this: Lorentz covariance only guarantees that for an arbitrary solution \( F \) of the physical equations in an inertial frame \( K \), stipulated to describe the physical system in question at rest in \( K \), the Lorentz boosted description, the one that has the same form as \( F \) expressed in the variables of another inertial frame \( K' \), is also a solution; while the essence of the relativity principle is that the Lorentz boosted description is not only a solution but it is identical to the one which describe the same phenomenon as \( F \) except that the physical system is now *in motion* relative to \( K \), co-moving as a whole with \( K' \).

Having the statement of the relativity principle clarified, the second part of the dissertation is concerned with the question of how to ascertain whether the relativity principle holds. It is pointed out that, even if the principle is often regarded as a meta-law, ultimately this is an empirical question. Interestingly, however, one hardly finds a reference to such an empirical confirmation. What we do find in the literature, instead, is a rather problematic account, for two reasons: 1) The relativity principle is simply equated with covariance (cf. Result 1). 2) The transformation rules for the physical quantities entering the physical equations, against which the equations should be covariant, are derived from the presumption that the equations are covariant—without any further reflection on whether the derived
transformation laws are the right ones. This is, we argue, a logical fallacy by which Lorentz covariance would reduce to a tautology. In contrast, the equations should not be covariant against some “well-selected” transformation rules, derived from the covariance assumption itself, but they must be covariant against the real physical transformation laws linking the results of measurements in different inertial frames. In this way, ascertaining whether the Lorentz covariance of physical equations is satisfied becomes equivalent with ascertaining the true transformation rules.

So, what are the transformation rules of the basic physical quantities? We point out that, primarily, this is an empirical question again. However, it is a natural idea to apply what J. S. Bell (1987) calls “Lorentzian pedagogy” according to which “the laws of physics in any one reference frame account for all physical phenomena, including the observations of moving observers”, that is, including what the transformation laws of quantities measured by different observers in different inertial frames are. As a case study for the Lorentzian pedagogy, we set out to derive the transformation laws of the basic quantities involved in classical electrodynamics, from the laws of electrodynamics in one single “rest” frame, and thereby ascertain whether the laws of electrodynamics are covariant. In spite of the fact that electrodynamics is considered as the prototypical example of a covariant theory, surprisingly, such an analysis has never been carefully performed.

The answer can be given by the laws of electrodynamics only if the question is properly formulated. We must be able to tell what the measurement operations are by means of which a moving observer determines the values of the electrodynamic quantities. Thus, first of all, we must know the operational definitions of these quantities themselves. As it turns out, however, to specify a precise, non-circular, coherent body of operational definitions for the electrodynamics quantities is a non-trivial problem. A possible construction is suggested (Gömöri and Szabó 2013).

The results of the analysis is the following. By applying the Lorentzian pedagogy, on the basis of the laws of electrodynamics in one single inertial frame, without presuming covariance, we show that the transformation rules of the electrodynamic quantities are identical with the ones obtained by presuming the covariance of the equations of electrodynamics, and thus covariance is indeed satisfied (Gömöri and Szabó 2013). In other words, we demonstrate:

**Result 2** The transformation laws of the basic electrodynamic quantities derived from presuming covariance, and thereby the covariance assumption itself, are consistent with the laws of electrodynamics in one single inertial frame.

According to Result 1, the satisfaction of covariance by no means imply the sat-
isfaction of the relativity principle. Is, then, the relativity principle a true law of
nature? Or is it, at least, derivable from the laws of physics in one single frame?
In trying to answer either of these questions, one encounters the following prob-
lem. The relativity principle, in line with our preliminary formulation, is about the
comparison of the behaviors of a physical system in two different states of motion:
one is in which the system as a whole is at rest in a frame \( K \), the other one is in
which it is as a whole in motion relative to \( K' \), co-moving with another frame \( K' \).
However, as it was pointed out in (Szabó 2004), there is no clear and unambiguous
meaning of the notion “a system as a whole in motion/rest”, even in very simple
situations. In the last part of the dissertation we demonstrate that this concept is
especially problematic in electrodynamics. We formulate a minimal condition that
an arbitrary solution \( F \) of the equations in question should satisfy in order for the
notion “a system as a whole in motion/rest” to meaningfully apply to the system in
question:

*Every solution \( F \) of the equations in question must describe a phe-
nomenon which can be meaningfully characterized as such that the phys-
ical system exhibiting this phenomenon is co-moving with some inertial
frame of reference.*

It is then argued that even this minimal condition is left unmet by a generic solution
of the equations of electrodynamics. We provide this argument in the more general
metaphysical context of the problem of persistence. First, we point out that the
concept of motion presupposes the concept of persistence. Then, formal conditions
are imposed in terms of the individuating properties of an entity expressing the fact
that the entity or at least its local parts persist. We call these conditions *equations
of persistence*. We then prove (Gömöri and Szabó 2014):

**Result 3** Most solutions of the equations of electrodynamics do not sat-
ify the equations of persistence if the individuating properties of the elec-
tromagnetic field are taken to be the electric and magnetic field strengths.

This suggest the following: 1) As persistence means existence in space and time, it is
problematic how an electromagnetic field can be regarded as a real entity existing in
space and time, contrary to the standard realistic interpretations of electrodynamics.
2) As the concept of a state of motion presupposes persistence, and the relativity
principle, according to our minimal requirement, presupposes the concept of a state
of motion, the principle of relativity remains an *incomprehensible* statement in the
case of a general electrodynamic system. This fact is of course in conflict with the
widespread view that the relativity principle is a universal principle valid for all phenomena.

References


