The relativity of inertia and reality of nothing

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Outline

Introduction

From absolute to relative inertia

- with general relativity Einstein responded to two troubling absolute features of Newtonian inertia by making inertia relative, to matter
  - perhaps imperfectly though, as a couple of freedom degrees—the polarization of gravitational waves—separate inertia from matter in his theory

- the relativity of inertia, perhaps even the full validity of Einstein's response, thus depends on the reality of gravitational waves—whose *Wegtransformierbarkeit* is hardly reassuring, however, and at best suggests a certain flimsiness

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Wegtransformierbarkeit

- various aspects—generation, energy, detection (?)—of the physics of gravitational waves are *wegtransformierbar*

- but should one be intolerant of *Wegtransformierbarkeit*?
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Two absolute annoyances

The two annoyances

- general relativity was Einstein's response to two absolute features of Newtonian mechanics that annoyed him

    1. observable effect, unobservable cause

    2. action without passion

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- the trouble with the absolute features of Newtonian mechanics (acceleration, force, laws *etc*.) is that they can be viewed as relative, but to something—affine structure or the *sensorium Dei* or absolute space—that isn't really there, that's too tenuous, invisible, mysterious, mathematical, ætherial, unmeasurable or theological to count as a cause, as a physically effective circumstance (for most empiricists at any rate)

- Einstein found the unobservability of the (Newtonian, or even Minkowskian) structure to which acceleration and inertia were referred so *erkenntnistheoretisch unbefriedigend* (1916) that **he made it relative**, to **matter**—which has a more obvious physical presence than the *sensorium Dei* or ∇

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Einstein (1916)
“Grundlage der allgemeinen Relativitätstheorie” p. 771-2

Aus welchem Grunde verhalten sich die Körper S_1 und S_2 verschieden? Eine Antwort auf diese Frage kann nur dann als erkenntnistheoretisch befriedigend anerkannt werden, wenn die als Grund angegebene Sache eine **beobachtbare Erfahrungstatsache** ist; denn das Kausalitätsgesetz hat nur dann den Sinn einer Aussage über die Erfahrungswelt, wenn als Ursachen und Wirkungen letzten Endes nur **beobachtbare Tatsachen** auftreten.

Die N e w t o nsche Mechanik gibt auf diese Frage keine befriedigende Antwort. Sie sagt nämlich folgendes. Die Gesetze der Mechanik gelten wohl für einen Raum R_1, gegen welchen der Körper S_1 in Ruhe ist, nicht aber gegenüber einem Raume R_2, gegen welchen S_2 in Ruhe ist. Der berechtigte G a l i l e ische Raum R_1, der hierbei eingeführt wird, ist aber eine **bloß fingierte** Ursache, keine beobachtbare Sache. Es ist also klar, daß die N e w t o nsche Mechanik der Forderung der Kausalität in dem betrachteten Falle nicht wirklich, sondern nur scheinbar Genüge leistet, indem sie die bloß fingierte Ursache R_1 für das beobachtbare verschiedene Verhalten der Körper S_1 und S_2 verantwortlich macht.

2. action without passion

- Einstein was also troubled by the fact that the absolute spacetime structure of Newtonian (or even Minkowskian) mechanics **acts on matter**, guiding it, **without reacting to it**

- the affine structure ∇ of the remedy he proposed, general relativity, acts on matter ($\nabla_{\dot\sigma}\dot\sigma = \mathbf{0}$) and is also constrained by it (through Einstein's equation)

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Einstein (1921)
Grundzüge der Relativitätstheorie p. 58

Dabei bedeutet „absolutum“ nicht nur „physikalisch-real“, sondern auch „in ihren physikalischen Eigenschaften selbständig, physikalisch bedingend, aber selbst nicht bedingt“. [. . .] widerstrebt es dem wissenschaftlichen Verstande, ein Ding zu setzen (nämlich das zeiträumliche Kontinuum), was zwar wirkt, auf welches aber nicht gewirkt werden kann.

Is inertia determined by matter?

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Matter

What's the matter?

- two main candidates (in general relativity):

    1. T^a_b
    2. $U^\mu_\nu = T^\mu_\nu + t^\mu_\nu$

- given the intimate relationship between matter and mass, it does not at first seem unreasonable to include

$$t^\mu_\nu = \frac{1}{2}\delta^\mu_\nu g^{\sigma\tau}\Gamma^\lambda_{\sigma\rho}\Gamma^\rho_{\tau\lambda} - g^{\sigma\tau}\Gamma^\mu_{\sigma\rho}\Gamma^\rho_{\tau\nu}, \tag{1}$$

  which represents the mass-energy-momentum of the gravitational field (and satisfies $\nabla_\mu T^\mu_\nu = \partial_\mu(T^\mu_\nu + t^\mu_\nu) = 0$)

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Matter of opinion

- but t^μ_ν is not a tensor; the right-hand side of (1) shows how it is related to the (notoriously untensorial) connection coefficients $\Gamma^\mu_{\nu\sigma}$
- in free fall, when they vanish, t^μ_ν does too
- the gravitational mass-energy represented by t^μ_ν is therefore a **matter of opinion**
  - no agreement as to its presence or absence
- I hesitate to count as matter something so tenuous it can be transformed away (besides which a superabundance of matter can bring the relationist uncomfortably close to his absolutist opponent, leaving them little room for debate—which has already been dismissed as "outmoded"; the surest way to hasten its **complete** demise is to impose agreement by a questionable appeal to a dubious object which can fill the universe with slippery coordinate-dependent matter that disappears in free fall and reappears under acceleration)
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Distant matter

- this talk is much more about general relativity than about Mach himself; it is certainly not about Mach's own formulations of his principles

- the vagueness and ambiguities of Mach's *Mechanik* have given rise to an abundance of 'Mach's principles'

- Mach and Einstein (1916) both speak of "distant" matter, which turns up in several versions of Mach's principle: one can say it is part of the 'Machian tradition,' conspicuously associated with Einstein, Wheeler, Barbour and others

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  1. the 'deceptive continuity' or 'average character' of ρ

  2. field-theoretical holism

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1. deceptive continuity

- Einstein's equation $G_{ab}(x) = T_{ab}(x)$ seems to express a circumscribed (direct) relationship of inertia to matter at (or around) point x

- the matter-energy-momentum tensor

$$T^{ab}(x) = \rho(x) V^a V^b,$$

  for instance, describing a 'dust' with density ρ and four-velocity V^a, would directly determine inertia at (or around) x, not at other points far away

- but much as in electromagnetism, the 'continuity' of ρ is deceptive

- once the scale is large enough to give a semblance of continuity to the density ρ, almost all the celestial bodies contributing to the determination of $\rho(x)$ will be very far, on any familiar scale, from x

- all the matter involved in the determination of $\rho(x)$ will be very close to x on the largest scales; but matter far from x even on those scales has a role too . . .

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2. field-theoretical holism

- general relativity is of course a field theory
  - all values of a field cannot be given freely and independently; assigning some will constrain others
  - fields are smooth, holistic entities, which can undulate, propagate perturbations, drag *etc*.

- even if the determination of inertia by matter is partly field-theoretical, holistic, non-local, global, **I will concentrate on the 'punctual' determination: on the arithmetic and comparison of freedom degrees at a point**

- words like "determination," "over/underdetermination" or "freedom" are often referred to a single point—by Einstein and others—even in field-theoretical contexts (where more holistic determinations are also at work), and seem neither illegitimate, meaningless nor inappropriate when applied so locally

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Is inertia determined by matter?

Inertia

Inertial motion

- is free and not forced by alien influences to deviate from its natural course
  - the characterisation is general
  - its terms take on specific meaning in particular theories

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Inertia in general relativity

- in general relativity, inertial motion is subject only to gravity and not to electromagnetic or other forces

- **inertia** can accordingly be identified with the structures that guide the free fall of bodies (perhaps the hands of clocks too) by determining the (possibly parametrised) geodesics they describe

- again there are two main candidates:

  1. affine structure

  2. projective structure

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Affine structure

- Einstein identifies inertia with the metric g, which in his theory—where ∇g vanishes (along with torsion)—corresponds to the affine structure given by the Levi-Civita connection

$$\nabla = \Pi_{\mathbf{0}},$$

with twenty degrees of freedom

- it gives the **parametrised** geodesics

$$\sigma_{\mathbf{0}} : (a, b) \rightarrow M : s_{\mathbf{0}} \mapsto \sigma_{\mathbf{0}}(s_{\mathbf{0}})$$

through

$$\nabla_{\dot{\sigma}_{\mathbf{0}}} \dot{\sigma}_{\mathbf{0}} = \mathbf{0},$$

and represents the 'inertia' of the parameter, hence of time or the hands of clocks, along with that of matter
(M being the differential manifold representing the universe)

Affine structure

- Einstein identifies inertia with the metric g, which in his theory—where ∇g vanishes (along with torsion)—corresponds to the affine structure given by the Levi-Civita connection

$$\nabla = \Pi_{\mathbf{0}},$$

  with twenty degrees of freedom

- it gives the **parametrised** geodesics

$$\sigma_{\mathbf{0}} : (a, b) \to M : s_{\mathbf{0}} \mapsto \sigma_{\mathbf{0}}(s_{\mathbf{0}})$$

  through

$$\nabla_{\dot{\sigma}_{\mathbf{0}}} \dot{\sigma}_{\mathbf{0}} = \mathbf{0},$$

  and represents the 'inertia' of the parameter, hence of time or the hands of clocks, along with that of matter
  (M being the differential manifold representing the universe)

Projective structure

- but time and clocks may be less the point here than plain free fall

- projective structure Π gives the 'generalised geodesics'

$$\sigma : (a, b) \to M : s \mapsto \sigma(s)$$

through

$$\nabla_{\dot{\sigma}}\dot{\sigma} = \lambda\dot{\sigma}$$

and just represents free fall, in other words the inertia of bodies alone, not of bodies **and** the hands of accompanying clocks

- one can say it is purely 'material,' rather than 'materio-chronometrical'

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Projective equivalence

- in the class
$$\Pi = \{\Pi_\alpha : \alpha \in \Lambda_1(M)\}$$
of connections projectively equivalent to ∇, a particular connection Π_α is singled out by a one-form α, which fixes the parametrisations s of all the generalised geodesics σ

- so projective structure has twenty-four degrees of freedom, four—namely $\alpha_0, \ldots, \alpha_3$—more than affine structure (where $\alpha_\mu = \langle \alpha, \partial_\mu \rangle$)

- one can write
$$\langle dx^\mu, \Pi_{\alpha\,\partial_\nu} \partial_\sigma \rangle = \mathit{\Gamma}^\mu_{\nu\sigma} + \delta^\mu_\nu \alpha_\sigma + \delta^\mu_\sigma \alpha_\nu,$$
$\mathit{\Gamma}^\mu_{\nu\sigma}$ being the components of the Levi-Civita connection

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Chronometrical acceleration

- the most meaningful part of the added freedom would appear to be the 'acceleration'

$$\lambda = -2\langle \alpha, \dot{\sigma} \rangle = -2\,\alpha_\mu \frac{d\sigma^\mu}{ds} = -\left(\frac{ds}{ds_{\mathbf{0}}}\right)^2 \frac{d^2 s_{\mathbf{0}}}{ds^2}$$

  of the parameter s along the generalised geodesic σ determined by Π_α

Second clock effect

- projective structure seems to represent inertia well

- but in fact not all of the freedom it has with respect to affine structure is empirically available
  - as second clock effects are never seen, α really should be exact
  - the four freedoms of α, that separate Π from $\nabla = \Pi_{\mathbf{0}}$, would be subject to the differential restriction $d\alpha = \mathbf{0}$ (which involves **six** independent quantities!)

- we have to make a choice, and will take affine structure to represent inertia (but if projective structure—duly restricted—is preferred, the arithmetic can be adjusted accordingly)

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Is inertia determined by matter?

Matter & inertia

How does matter constrain inertia?

- through Einstein's equation $G_{ab} = T_{ab}$

- inertia (affine structure) is hidden in the Einstein tensor

$$G_{ab} = R_{ab} - \frac{1}{2} R g_{ab},$$

where $R_{ab} = R^c_{\ acb}$ is the Ricci tensor, $R = g^{ab} R_{ab}$ his scalar, and $R^a_{\ bcd}$ the Riemann tensor

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Curvature and affine structure

- the relationship between curvature and inertia is given by

$$B^{\mu}_{\nu\kappa\lambda} = 2\Gamma^{\mu}_{\nu[\lambda,\kappa]} + \Gamma^{\tau}_{\nu\lambda}\Gamma^{\mu}_{\tau\kappa} - \Gamma^{\tau}_{\nu\kappa}\Gamma^{\mu}_{\tau\lambda}$$

- the curvature tensor of an arbitrary connection has ninety-six (6×4^2) independent quantities, eighty if the connection is symmetric (*i.e.* without torsion), only twenty if it is also metric ($\nabla g = 0$)—in which case B^{a}_{bcd} becomes the Riemann tensor R^{a}_{bcd}

- the (metric, symmetric) connection also has twenty degrees freedom

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The underdetermination of inertia by matter

- to a single contraction R_{ab} there correspond many Riemann tensors R^a_{bcd} (and many connections and metrics)

- to reach the ten freedom degrees of R_{ab} (and G_{ab} and T_{ab}) the contraction eliminates ten of the twenty freedoms of R^a_{bcd}, which can be seen as ending up in the Weyl tensor

$$C_{abcd} = R_{abcd} - g_{a[c}R_{d]b} + g_{b[c}R_{d]a} + \frac{1}{3}Rg_{a[c}g_{d]b}$$

- this underdetermination will disappoint the relationist; but eight degrees of freedom can be eliminated by suitable gauge choices (details in Afriat & Caccese (2009)), leaving two, which represent the polarization of gravitational waves

- to dismiss them as physically meaningless the relationist will have to claim that **gravitational waves aren't really there**, since they can be **transformed away**

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Wegtransformierbarkeit

General covariance

- the physics of gravitational waves is surprisingly vulnerable to transformations
- the
  - generation
  - energy-momentum
  - detection (?)

  of gravitational waves are not **generally** covariant
- by attributing physical meaning only to what is generally covariant and cannot be transformed away, the relationist can question the generation, energy-momentum and perhaps even the detection (?) of gravitational waves

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“the sun stood still, and the moon stayed” (Joshua x, 13)

- the binary star PSR1916 +13 loses kinetic energy as it spirals inwards
- if energy is conserved, the lost kinetic energy will be transformed and **radiated**
- but the ‘spiral’ can be transformed away by suitable substitutions, which leave the pulsars where they are at, say, $(t, 1, 0, 0)$ and $(t, 0, 0, 0)$
  - since they describe geodesics they don’t even accelerate
- if they neither move nor accelerate, how can they lose an energy **of motion** they never had in the first place?
- and the conservation law invoked to turn any lost kinetic energy into radiation **isn’t generally covariant** either (since it involves a distant comparison of direction, which cannot, on a curved manifold, be both generally covariant and unambiguously integrable)

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The energy-momentum of gravitational waves

- again, the energy-momentum of gravitational waves is typically represented by the pseudotensor
$$t^\mu_\nu = \frac{1}{2}\delta^\mu_\nu g^{\sigma\tau}\Gamma^\lambda_{\sigma\rho}\Gamma^\rho_{\tau\lambda} - g^{\sigma\tau}\Gamma^\mu_{\sigma\rho}\Gamma^\rho_{\tau\nu},$$
which can also be transformed away: in free fall it vanishes

The *Wegtransformierbarkeit* of detection

- a detector is made up of (say) two masses, which we can imagine in the middle of nowhere (the earth's gravitational field being hardly the point here)

- the gravitational wave is supposed to wiggle them; but with respect to what coordinate system?

- again, there are coordinates with respect to which the masses stay put at $(t, 1, 0, 0)$ and $(t, 0, 0, 0)$, for instance

- both masses describe geodesics; how can objects wiggle if they neither move nor accelerate?

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Geodesic deviation

- the absolultist will claim the wiggling is absolutely measured by the (nonvanishing) relative acceleration

$$\frac{d^2\xi^a}{d\tau^2} = R^a_{0b0}\xi^b,$$

  which, being tensorial, cannot be transformed away

- this puts the relationist into something of a corner, *mathematically*—from which he can emerge *experimentally* by pointing out that the acceleration in question, however tensorial and covariant, has yet to be *measured*

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Tangle of belief

- besides which, belief is an inextricable tangle
  - if the generation and even the very stuff of gravitational waves can be transformed away at the stroke of a pen, what's left?
  - will varied speculation about the outcome of yet another attempt (after several failures) to find the weakest of signals, completely drowned in noise, be enough to dispel uncertainty and guarantee belief?
  - won't whatever speculative belief one can muster be tangled up with—and indeed undermined by—all the subtle perplexities of invariance, conservation and *Wegtransformierbarkeit*?

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Agreement and reality

Invariance and covariance

- covariance and invariance are rightly confused in much of the literature, and here too

- whether it is a mere number or the look, shape, *Gestalt* or syntax of an expression that remains unchanged is less the point than the generality—**complete** or **merely Lorentz**, for instance—of the transformations at issue

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Reality and invariance

- general relativity has been at the centre of a tradition—conspicuously associated with Hilbert (1917), Cassirer (1921), Einstein (1922) himself eventually, Langevin (1922), Meyerson (1925), Russell (1927) and Weyl (1927)—linking physical reality or objectivity to appropriate transformation properties, to something along the lines of invariance or covariance

- roots can be sought
  - as far back as Democritus, who is said to have claimed that “sweet, bitter, hot, cold, colour” are mere opinion, “only atoms and void”—concerning which there ought in principle to be better agreement—“are real”
  - or more recently (1872) in Felix Klein’s ‘Erlangen programme,’ which based geometrical relevance on invariance under the groups he used to classify geometries

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Russell

- in his version of neutral monism, Bertrand Russell (1912, 1921, 1927, 1956) identified objects with their various appearances from different points of view—not really an association of invariance and reality, but an attempt to transcend the misleading peculiarities of individual perspectives nonetheless

Hilbert (1917)
“Die Grundlagen der Physik (Teil II)”

Die Formen, in denen physikalisch sinnvolle, d. h. invariante Aussagen mathematisch zum Ausdruck gebracht werden können, sind sehr mannigfaltig: [. . .]

Levi-Civita (1917)
“Sulla espressione analitica spettante al tensore ...”

L’idea di un tensore gravitazionale fa parte della grandiosa costruzione di Einstein. Però la definizione propostane dall’Autore non può risguardarsi definitiva. Anzi tutto, dal punto di vista matematico, le fa difetto quel carattere invariantivo che dovrebbe invece necessariamente competerle secondo lo spirito della relatività generale.

Schrödinger (1918)
“Die Energiekomponenten des Gravitationsfeldes”

Dieses Ergebnis scheint mir [. . .] von ziemlicher Bedeutung für unsere Auffassung von der physikalichen Natur des Gravitationsfeldes. Denn entweder müssen wir darauf verzichten, in den durch die Gleichung (2) definierten t^{α}_{σ} die Energiekomponenten des Gravitationsfeldes zu erblicken; damit würde aber zunächst auch die Bedeutung der „Erhaltungssätze“ [. . .] fallen und die Aufgabe erwachsen, diesen integrierenden Bestandteil der Fundamente neuerdings sicher zu stellen. – Halten wir jedoch an den Ausdrücken (2) fest, dann lehrt unsere Rechnung, daß es wirkliche Gravitationsfelder (d. i. Felder, die sich nicht „wegtransformieren“ lassen) gibt, mit durchaus verschwindenden oder richtiger gesagt „wegtransformierbaren“ Energiekomponenten; Felder, in denen nicht nur Bewegungsgröße und Energiestrom, sondern auch die Energiedichte und die Analoga der M a x w e l lschen Spannungen durch geeignete Wahl des Koordinatensystems für endliche Bezirke zum Verschwinden gebracht werden können.

Schrödinger (1926)
“Quantisierung als Eigenwertproblem (Zweite Mitteilung)”

[. . .] wenn etwas Sinnvolles, d. h. Invariantes resultieren soll.

Einstein

- first seemed happy to extend reality to objects with the wrong transformation properties . . .

Einstein (January 1918)
"Über Gravitationswellen"

[Levi-Civita] (und mit ihm auch andere Fachgenossen) ist gegen eine Betonung der Gleichung [$\partial_\nu(\mathfrak{T}_\sigma^\nu + \mathfrak{t}_\sigma^\nu) = 0$] und gegen die obige Interpretation, weil die $\mathfrak{t}_\sigma^\nu$ keinen T e n s o r bilden. Letzteres ist zuzugeben; aber ich sehe nicht ein, warum nur solchen Größen eine physikalische Bedeutung zugeschrieben werden soll, welche die Transformationseigenschaften von Tensorkomponenten haben.

Einstein (May 1918)
“Der Energiesatz in der allgemeinen Relativitätstheorie”

Diese Formulierung stößt bei den Fachgenossen deshalb auf Widerstand, weil $(\mathfrak{U}_\sigma^\nu)$ und $(\mathfrak{t}_\sigma^\nu)$ keine Tensoren sind, während sie erwarten, daß alle für die Physik bedeutsamen Größen sich als Skalare und Tensorkomponenten auffassen lassen müssen.

Einstein (November 1918) “Dialog über Einwände gegen die Relativitätstheorie”

Zunächst muß ich darauf aufmerksam machen, daß die Unterscheidung real – nichtreal uns wenig fördern kann. In bezug auf K' „existiert“ das Gravitationsfeld in demselben Sinne wie irgendwelcher andere physikalische Gegenstand, der bloß mit bezug auf ein Koordinatensystem definiert werden kann, trotzdem es in bezug auf das System K nicht vorhanden ist. Hierin liegt keine besondere Merkwürdigkeit, wie man leicht an folgendem, der klassischen Mechanik entnommenen Beispiel erkennt. Niemand zweifelt an der „Realität“ der kinetischen Energie, da man sonst dazu käme, die Realität der Energie überhaupt zu leugnen. Es ist aber klar, daß die kinetische Energie eines Körpers von dem Bewegungszustande des Koordinatensystems abhängig ist; durch passende Wahl des letzteren kann man es offenbar herbeiführen, daß die kinetische Energie der fortschreitenden Bewegung eines Körpers in einem bestimmten Augenblick irgend einen vorgegebenen, positiven Wert oder den Wert Null annimmt. [...]

Einstein (November 1918)
“Dialog über Einwände gegen die Relativitätstheorie”

Statt zwischen „real“ und „nichtreal“ wollen wir deutlicher unterscheiden zwischen Größen, welche dem physikalischen System als solchem zukommen (unabhängig von der Wahl des Koordinatensystems) und solche Größen, welche vom Koordinatensystem abhängen. Das Nächstliegende wäre, zu verlangen, daß die Physik in ihre Gesetze nur Größen der ersteren Art einführen solle. Es hat sich jedoch erwiesen, daß dieser Weg praktisch nicht realisierbar ist, wie schon die Entwicklung der klassischen Mechanik deutlich gezeigt hat. [. . .] Sie kann das Koordinatensystem nicht entbehren, muß also in den Koordinaten Größen verwenden, die sich nicht als Ergebnisse von definierbaren Messungen auffassen lassen. [. . .] Nur gewissen, im allgemeinen ziemlich komplizierten Ausdrücken, die aus Feldkomponenten und Koordinaten gebildet werden, entsprechen vom Koordinatensystem unabhängig meßbare (d. h. reale) Größen. So entspricht beispielsweise den Komponenten des Gravitationsfeldes in einem Raum-Zeitpunkt noch keine von der Koordinatenwahl unabhängige Größe; dem Gravitationsfeld **an einer Stelle** entspricht also noch nichts „physikalisch Reales“, wohl aber diesem Gravitationsfelde in Verbindung mit anderen Daten. Man kann deshalb weder sagen, das Gravitationsfeld an einer Stelle sei etwas „Reales“, noch es sei etwas „bloß Fiktives“.

but then . . .

Einstein (1921)
Grundzüge der Relativitätstheorie p. 5

Verschiedene Menschen können mit Hilfe der Sprache ihre Erlebnisse bis zu einem gewissen Grade miteinander vergleichen. Dabei zeigt sich, daß gewisse sinnliche Erlebnisse verschiedener Menschen einander entsprechen, während bei anderen ein solches Entsprechen nicht festgestellt werden kann. Jenen sinnlichen Erlebnissen verschiedener Individuen, welche einander entsprechen und demnach in gewissem Sinne überpersönlich sind, wird eine Realität gedanklich zugeordnet. Von ihr, daher mittelbar von der Gesamtheit jener Erlebnisse, handeln die Naturwissenschaften, speziell auch deren elementarste, die Physik. Relativ konstanten Erlebnis-komplexen solcher Art entspricht der Begriff des physikalischen Körpers, speziell auch des festen Körpers.

Interpersonal coincidence

- admittedly he only speaks of the “sensory experiences of different people” and not explicitly of the transformations that convert sensations between them, nor of general covariance for that matter
- not explicitly, but almost
- he eventually mentions physics
- **experiences** in physics can be called **measurements**, and they tend to yield numbers
- theory provides the transformations converting the numbers measured by one person into those measured by another
- for measurements yielding a single number, the interpersonal ‘coincidence’ at issue can be interpreted as numerical equality: only genuine **scalars**—which are the same for everyone—would belong to the ‘superpersonal reality’

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Coincidence of more general measurements

- with measurements that produce **arrays** of numbers the notion of 'coincidence' upon which reality rests is less straightforward
- it will no longer be a matter of numerical equality, for each component of the complex (which would be unsatisfiably strong)
- it will have to be a more holistic kind of correspondence, to do with the way the components change together
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Characteristic transformations

- of course the characteristic class of transformations will not be the same in every theory; in general relativity it is the most general class (of transformations satisfying mimimal requirements of smoothness)

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Einstein (1921)

Grundzüge der Relativitätstheorie p. 13

Offenbar **haben** in der euklidischen Geometrie **nur solche** (und alle solche) **Größen eine objektive** (von der besonderen Wahl des kartesischen Systems unabhängige) **Bedeutung, welche sich durch eine Invariante** (bezüglich linearer orthogonaler Koordinaten) **ausdrücken lassen**. Hierauf beruht es, daß die Invariantentheorie, welche sich mit den Strukturgesetzen der Invariante beschäftigt, für die analytische Geometrie von Bedeutung ist.

(my emphasis)

what made him change his mind?

Cassirer (August 1920)
Zur Einstein'schen Relativitätstheorie p. 2

A l b e r t E i n s t e i n hat den folgenden Aufsatz im Manuskript gelesen und ihn durch einzelne kritische Bemerkungen, die er an die Lektüre geknüpft hat, gefördert [. . .].

From things to abstract structures

- Cassirer welcomed general relativity as confirming, even consolidating a philosophical and scientific tendency he had already described in *Substanzbegriff und Funktionsbegriff*
  - a tendency that replaced the obvious things and substances filling the world of common sense, with abstract theoretical entities, relations and structures

- even the cruder objects of the naïve previous ontology derived their reality from ‘invariances’ of sorts, but only apparent ones—mistakenly perceived by the roughness of our unassisted senses—to be replaced by the more abstract and accurate invariants of modern theory

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Truth and general covariance

- Cassirer (1921) even associated **truth** with general covariance

> Die Raum- und Zeitmaße in jedem einzelnen System bleiben relativ: aber die Wahrheit und Allgemeinheit, die der physikalischen Erkenntnis nichtsdestoweniger erreichbar ist, besteht darin, daß alle diese Maße sich wechselseitig entsprechen und einander nach bestimmten Regeln zugeordnet sind.

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The whole truth

- and truth is not fully captured by an incomplete collection of perspectives; nothing short of **all of them** will give the whole truth

  Dieser wird weder durch die Beobachtungen und Messungen eines Einzelsystems, noch selbst durch diejenigen beliebig vieler solcher Systeme, sondern nur durch die wechselseitige Zuordnung der Ergebnisse a l l e r möglichen Systeme erreicht und gewährleistet.

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General (not partial) covariance

- anything less than **general** covariance isn't good enough: U^{μ}_{ν}, t^{μ}_{ν} and $\Gamma^{\mu}_{\nu\kappa}$ are Lorentz—even 'linearly'—covariant, in the sense that they're tensors with respect to $\mathbb{GL}(4, \mathbb{R})$; but

  > Die Messung in e i n e m System, oder selbst in einer unbeschränkten Vielheit irgendwelcher „berechtigter" Systeme, würde schließlich immer nur Einzelheiten, nicht aber die echte „synthetische Einheit" des Gegenstandes ergeben.

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Too late

- but—returning to Einstein—it was too late to repent: the damage had been done, the cause was already lost, and indeed the lenity Einstein promoted in 1918 continues to this day

- general covariance is often disregarded or violated in general relativity
  - if a calculation works in one coordinate system, too bad if it doesn't in another
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Principles *vs*. pragmatism

- to question the reality, generation and detection of gravitational waves, the relationist would demand general covariance—one of the central **principles** of general relativity—**as a matter of principle**

- his absolutist opponent can fall back on the more tolerant day-to-day pragmatism of the practicing, calculating, approximating physicist, who views the theory more as an instrumental collection of recipes, perturbation methods, tricks and expedients—by which even the most sacred principles can be circumvented or even sacrificed—than as a handful of fundamental and inviolable axioms from which all is to be deduced:

  – general covariance may well have provided useful guidance over eighty years ago, but surely general relativity has now outgrown it . . .

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Wegtransformierbarkeit and inconsistency

- but perhaps there's more at issue than just opinion or perspective

- much as one can wonder whether the different witnesses in Rashomon are *lying*, rather than expressing reasonable differences in perspective; whether their versions are *incompatible*, not just coloured by stance and prejudice—here the relationist may even complain about something as strong as *inconsistency*, while his opponent sees no more than rival points of view

- of an object that's at rest in one system but not in another one can say that

  – *it's moving & isn't*

  which sounds contradictory

- consistency can of course be restored with longer statements referring the motion to the different systems, but the contradictory short statements are not without significance

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Consistency and reality

- consistency and reality are not related; consistency is certainly bound up with mathematical existence, for which it has long been considered necessary—perhaps even sufficient (Poincaré?)

- and in mathematical physics, how can the physical significance of a mathematical structure not be compromised by a kind of inconsistency?

- if inconsistency prevents part of a formalism from 'existing,' how can it represent reality?

- the relationist will argue that an object, like t^{μ}_{ν}, whose existence is complicated—perhaps even compromised—by an 'inconsistency' of sorts (*it's there & isn't*), cannot be physically meaningful

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So?

- the inertia of Newtonian/Minkowskian mechanics is absolute, in other words determined by an empirically inaccessible structure, that acts without response: it guides matter without reacting to it
- Einstein tried to remedy by making inertia relative, to matter, which has a more obvious physical presence, and furthermore **reacts**
- so **is inertia determined by matter** in general relativity?
- gravitational waves seem to obstruct its full determination
- but they appear to be so flimsy and insubstantial they can be **transformed away**
  - their generation and energy-momentum **aren't generally covariant**
- an (unfashionable?) insistence on general covariance can make the relativization of inertia proposed by Einstein seem rather complete and satisfactory

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