The relativity of inertia and reality of nothing

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Outline

Introduction

Newton

- Newton (to whom I'll devote a few screens to set up the problem possibly solved by Einstein) appears to distinguish between an **absolute** and a **relative** acceleration

- the determination of acceleration (perhaps through force, to which according to the second law it is proportional) is at the core of his whole programme

- relative acceleration is measurable, **but is the wrong one**; and the measurement of absolute acceleration is a good deal less straightforward . . .

- the basic problem is the absoluteness, the unobservability of the structure (we now call affine) giving absolute inertia and acceleration

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Einstein and relative intertia

- Einstein (1916, 1921) recognises the problem and responds with **general relativity**, in which inertia, constrained by matter, is less absolute

- but what's the exact nature of the constraint? to what extent is the new inertia really **relative** (to matter)?

- we'll see that matter **underdetermines inertia by two quantities**, which represent the polarization of gravitational waves

- the full relativity of inertia, perhaps even the 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

- indeed various aspects—generation, energy, detection (?)—of the physics of gravitational waves appear to be *wegtransformierbar*

- but should one be intolerant of *Wegtransformierbarkeit*?

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Newton

Newton, *Principia*
(from the *scholium* after the definitions)

Causæ, quibus motus veri et relativi distinguuntur ab invicem, sunt vires in corpora impressæ ad motum generandum. Motus verus nec generatur nec mutatur nisi per vires in ipsum corpus motum impressas: at motus relativus generari et mutari potest sine viribus impressis in hoc corpus. Sufficit enim ut imprimantur in alia solum corpora ad quæ fit relatio, ut ijs cedentibus mutetur relatio illa in qua hujus quies vel motus relativus consistit. Rursus motus verus a viribus in corpus motum impressis semper mutatur, at motus relativus ab his viribus non mutatur necessario. Nam si eædem vires in alia etiam corpora, ad quæ fit relatio, sic imprimantur ut situs relativus conservetur, conservabitur relatio in qua motus relativus consistit. Mutari igitur potest motus omnis relativus ubi verus conservatur, et conservari ubi verus mutatur; et propterea motus verus in ejusmodi relationibus minime consistit.

where do I see the two accelerations (absolute & relative)?

(same passage)

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Motus

- is always translated as something like **motion** (or *Bewegung* or *moto* or *mouvement etc*.)

- works in some contexts but not others

- very briefly, Newton seems first to specify that **change** (or generation) of *motus* is at issue; having settled that, he just writes *motus*—thus ensuring limitless confusion, for centuries
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Three cases

1. the absolute acceleration of a body requires the application of a force on the body itself
   (*Motus verus nec generatur nec mutatur nisi per vires in ipsum corpus motum impressas* [. . .] *motus verus a viribus in corpus motum impressis semper mutatur*)

2. to produce relative acceleration the force can act on another body
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3. relative acceleration can even be cancelled if force is applied to both bodies
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The two accelerations

- since the distinction can't be drawn precisely enough using resources provided by Newton, we'll have to be anachronistic

- the acceleration d^2x^μ/dt^2 is **relative** (to the coordinates x^μ) while the acceleration

$$A^\mu = \frac{d^2x^\mu}{dt^2} + \sum_{\nu,\sigma=1}^{3} \Gamma^\mu_{\nu\sigma}\frac{dx^\nu}{dt}\frac{dx^\sigma}{dt}$$

  ($\mu = 1, 2, 3$ and the time t is absolute) is **absolute** in the sense that, being represented by a tensor, it is generally covariant

- for the second term we can write

$$\Xi^\mu = \sum_{\nu,\sigma=1}^{3} \Gamma^\mu_{\nu\sigma}\frac{dx^\nu}{dt}\frac{dx^\sigma}{dt}$$

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The three cases brought up to date

1. $[A^\mu \neq 0] \Rightarrow [F^\mu \neq 0]$ (since $F^\mu = mA^\mu$)

2. $[d^2x^\mu/dt^2 \neq 0] \not\Rightarrow [A^\mu \neq 0]$, in other words one can have $d^2x^\mu/dt^2 = -\Xi^\mu$

3. $[d^2x^\mu/dt^2 = 0] \not\Rightarrow [A^\mu = 0]$, in other words one can have $A^\mu = \Xi^\mu$

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Hunc enim in finem . . .

- making sense of acceleration is at the heart of his whole programme:

  $\boxed{\text{Motus}}$ autem veros ex eorum causis, effectibus, et apparentibus differentiis colligere, et contra ex motibus seu veris seu apparentibus eorum causas et effectus, docebitur fusius in sequentibus. Hunc enim in finem Tractatum sequentem composui.

  (end of the same *scholium*)

Measurement of acceleration

- the relative acceleration d^2x^μ/dt^2 is directly measurable

- but Newton disdains relative quantities (as **vulgar** *etc.*)

- what he's really after is the absolute acceleration $A^\mu = d^2x^\mu/dt^2 + \Xi^\mu$

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Independent measures?

- suppose the mass m is measurable **independently of force & acceleration** (of course it isn't); and that $m = 1$

- so $F^\mu = A^\mu$

- if the force F^μ were independently mesurable, we'd have A^μ, and indeed Ξ^μ ($d^2x^\mu/dt^2 = A^\mu - \Xi^\mu$ being directly mesurable)

- but neither F^μ nor m nor A^μ nor Ξ^μ are independently measurable

- the basic problem is the unobservability of Ξ^μ, in other words of affine (or inertial) structure $\Gamma^\mu_{\nu\sigma}$

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Wrong acceleration

- so Newton would like to measure the absolute acceleration A^μ, but can't (since $\Gamma^\mu_{\nu\sigma}$ is unobservable)

- and he doesn't care about the relative acceleration d^2x^μ/dt^2

- the matter doesn't seem to bother him particularly ... but Einstein ...

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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)
Vier Vorlesungen 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

- so like Einstein I'll take T^a_b rather than $U^\mu_\nu = T^\mu_\nu + t^\mu_\nu$ to represent matter

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- so like Einstein I'll take T^a_b rather than $U^\mu_\nu = T^\mu_\nu + t^\mu_\nu$ to represent matter

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

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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

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

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
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- 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

$$\langle dx^\mu, \Pi_{\alpha\, \partial_\nu} \partial_\sigma \rangle = \mathit{\Gamma}^\mu_{\nu\sigma} + \delta^\mu_\nu \alpha_\sigma + \delta^\mu_\sigma \alpha_\nu,$$

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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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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's 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, 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 transformation
- the
  - generation
  - energy-momentum
  - detection (?)

  of gravitational waves do not seem to be **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 absolutist 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

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

Reality and invariance

- general relativity has been at the centre of a tradition—conspicuously associated with Hilbert (1917), Cassirer (1921), Einstein (1921) 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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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_σ^α 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 $[\partial_\nu(\mathfrak{T}^\nu_\sigma + \mathfrak{t}^\nu_\sigma) = 0]$ und gegen die obige Interpretation, weil die $\mathfrak{t}^\nu_\sigma$ 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.

but then . . .

Einstein to Painlevé (7 December 1921)

Wenn man in der zentral-symmetrischen statischen Lösung für ds^2 statt r irgend eine Funktion von r einfügt, so erhält man keine *neue* Lö[su]ng, **da die Grösse r an sich keinerlei physikalische Bedeutung hat**, sondern nur die Grösse ds selbst, oder besser gesagt das Netz aller ds in der vierdimensionalen Mannigfaltigkeit. Es muss stets im Auge behalten werden, dass **die Koordinaten an sich keine physikalische Bedeutung besitzen**, das heisst, dass **sie keine Messresultate darstellen**, **nur Ergebnisse, die durch Elimination der Koordinaten erlangt sind, können objektive Bedeutung beanspruchen**. Die metrische Interpretation der Grösse ds ist ferner keine „pur imagination“, sondern der innerste Kern der ganzen Theorie. Die Sache verhält sich nämlich wie folgt: Gemäss der speziellen Relativitäts-Theorie sind die Koordinaten x, y, z, t mittelst relativ zum Koordinaten-System ruhenden Uhren unmittelbar messbar, also hat auch die Invariante ds, definiert durch die Gleichung $ds^2 = dt^2 - dx^2 - dy^2 - dz^2$ die Bedeutung eines Messergebnisses.

Convenient new stance

- this last Einstein would be able to (or rather have to) say that gravitational waves ***keine physikalische Bedeutung besitzen***—the very gravitational waves that stand in the way of a full determination of inertia

- and if inertia is fully determined by matter his theory becomes a satisfactory and complete response to the two absolute annoyances that so troubled him some screens ago

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Can nothing be real?

- Einstein 1918: why not?

- Einstein 1921: of course not!

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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 $\mathit{\Gamma}^{\mu}_{\nu\kappa}$ 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 a century ago, but surely general relativity has now outgrown it . . .

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- 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 get in the way of its full determination
- but they appear to be so flimsy and insubstantial they can be **transformed away**
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