Science would be an easy matter if the fundamental states of nature expressed themselves candidly and frankly in experience. In that case we could simply collect the truths lying ready before our eyes. In fact, however, nature is more reserved and shy, and its fundamental states often appear in masquerade. Put less metaphorically, there is no straightforward one-to-one correspondence between a theoretical and an empirical state. One of the reasons for the lack of such a tight connection is that distortions may enter into the relation between theory and evidence, and these distortions may alter the empirical manifestation of a theoretical state. As a result, it is in general a nontrivial task to excavate the underlying state from distorted evidence.

The problem of distortions is by no means restricted to the realm of the physical sciences. On the contrary, the difficulty of guaranteeing the reliability of the data pervades all science, including psychology. Consider the example of Freud's method of free association. This method is supposed to bring to light cognitive material originating in the dark depths of the unconscious. The trustworthiness of the conclusions based on this material is crucially dependent on whether it survives essentially intact the analyst's attempts to lift it to the waking mind. But as Adolf Grünbaum has made convincingly clear, the analyst's "maeutic" interventions in fact contribute to the distortion of the data they purportedly unearth. By emphasizing particular
aspects of the reported thoughts and feelings at the expense of others and by posing leading questions, the analyst exercises a suggestive influence on the docile patient on her couch. The result is that the interpreted data are seriously contaminated by the theoretical expectations and thus tend to comply with them (see Grünbaum 1984, 235, 277). So, we have a situation in which the influence of a distorting factor hinders the reliable evaluation of states posited within a theory.

This essay will discuss the problem of extracting theoretical states in the presence of perturbations. I will not be concerned with the difficulty of ascertaining hidden mental states; rather, I address the analogous difficulty as it shows up regarding the measurability of geometric relations. In spite of this difference in content, Grünbaum’s work is of substantial help. More specifically, I will consider Grünbaum’s discussion of a problem raised by Einstein. Einstein argued that physical geometry cannot be established empirically without invoking the entire system of physical laws. This claim is backed by an analysis of measuring procedures for geometric quantities that is modeled on Reichenbach’s argument for the conventionality of geometry. Einstein’s point here is the existence of measurement distortions induced by substance-specific effects such as temperature variations. These distortions vitiate the separate determination of physical geometry. Grünbaum, by contrast, holds that there is a way out of the perturbation problem posed by Einstein. He argues that geometric influences and substance-specific distortions can be disentangled empirically. I will present Grünbaum’s views on that matter and try to evaluate them in light of some more recent physical and philosophical developments. For that purpose I will first sketch Einstein’s argument and relate it to its conceptual context, namely, Reichenbach’s conventionality thesis of physical geometry.

Reichenbach: Universal Forces and the Conventionality of Geometry

The problem of the conventionality of geometry originated with Poincaré’s consideration of possible distortions of measuring rods. He analyzed the way in which such distortions might influence the results obtained and their physical interpretation, and he argued that certain generally occurring deformations of the rods could easily be
explained away by introducing a geometric curvature. Both interpretations would be empirically indistinguishable.

Reichenbach elaborated Poincaré’s analysis and gave the conventionality thesis its familiar form. In the first place he coined the distinction between differential and universal forces. Differential forces are characterized by the fact that they act differently on different substances. Accordingly, the deformation of measuring rods produced by them depends upon the material employed and is thus easily detectable and correctable. Matters are different, however, with respect to universal forces. The latter are supposed to act on all materials alike, and this implies that their presence or intensity is impossible to detect directly by empirical means. However, indirect indications may exist for them. If the universal force field is inhomogeneous (i.e., if its strength is position-dependent), it can induce relative deformations in suitably arranged rods. Hence a gradient of the force field is associated with empirically accessible features; universal forces are not always coincidence-preserving.

Reichenbach’s proposal for handling universal forces is to remove them by way of a methodological decision. Though we are not forced by the facts to do so, it is advisable (for reasons that will soon become clear) to set these forces equal to zero. This leads to the definition of the rigid body. A rigid body is a solid body that satisfies the following two conditions: (1) All possibly present differential deformations are corrected, and (2) all universal forces are set equal to zero (see Reichenbach [1928] 1965, 32–39).

Reichenbach’s analysis (as far as hitherto presented) can be summarized by the following three assertions: First, the measurement of metric relations is dependent upon a stipulation about the presence or absence of universal forces. Accordingly, a conventional element is involved in empirically establishing the metric. Second, after such a stipulation has been accepted, the metric (together with all geometric relations derived from it) is uniquely fixed. Third, it is recommended that we make this stipulation such that universal forces vanish.

What does it mean to set equal to zero a force that may lead to empirically detectable deformations? The point of Reichenbach’s recommendation becomes clear if one considers a serious candidate for a universal force, namely, gravitation. Gravitational forces indeed act on all materials alike. And setting universal forces equal to zero is intended to capture the gist of Einstein’s geometrization of gravitation.
This geometrization amounts to interpreting gravitation (at least locally) not as a physical force but as a manifestation of spacetime structure; geometric curvature, not a physical force, underlies the well-known empirical effects of gravitation.

Setting universal forces equal to zero accordingly means that the effects of gravitation are not to be attributed to a deforming force but to the metric structure itself. It means that gravitational effects on measuring rods are not corrected but viewed as veridical indications of the prevailing (nonflat) geometry. After all, it hardly makes sense to correct influences of spacetime on spacetime measurements. It is precisely this geometrization that distinguishes Einstein's approach from Newton's. So Reichenbach's (ibid., 38–39, 293–94) rule is supposed to furnish a justification of the former, although this justification is itself dependent upon a conventional decision.¹

Now that we know what Reichenbach is getting at, let us turn to the logical structure of his argument. The measurement of the prevailing geometric relations may be distorted by a universal force whose action can only be established or excluded by comparing the empirically obtained (and possibly distorted) relations with the actual ones. This comparison would enable one to correct these distorting influences. Obviously, on the other hand, such a comparison requires that the actual geometry already be known, but one can only come to know it by carrying out measurements. So there is a mutual dependence between two quantities, the universal for $F_U$ and the metric tensor $g_{ab}$, each of which can only be determined by recourse to the other. This amounts to a correction circularity that is dissolved (if one adopts Reichenbach's rule) by the decision not to correct at all.

In order to make things more perspicuous I want to introduce the concept of a "self-referential" distortion. Effecting the correction of a self-referential distortion requires recourse to the very same quantity whose measurement is to be corrected. Apparently, based on the foregoing discussion, a universal force is a self-referential distortion of the metric. The influence of a universal force on the metric can only be corrected by resorting in turn to the metric. More generally, it is sufficient for a self-referential distortion that there exists a reciprocal dependence between two quantities such that the reliable (i.e., corrected) measurement of either necessarily presupposes a reliable (i.e., corrected) measurement of the other. So Reichenbach's argument amounts to the claim that a self-referential distortion is involved in
empirically determining physical geometry, which leads to a circularity. And for that reason, geometry contains a conventional element.

**Einstein: Differential Forces and the Conventionality of Geometry**

In a discussion of Reichenbach's interpretation of geometry, Einstein objects to Reichenbach’s views claiming that even after universal forces have been excluded, physical geometry is still underdetermined. This means Einstein opposes the second of Reichenbach's assertions, namely, the claim that, after a decision about universal forces has been made, the actual geometry is unambiguously given. Einstein's point is that differential forces are not as easily detectable and correctable as Reichenbach assumed. Einstein's argument can be reconstructed to the effect that differential corrections, too, are in fact self-referential. His view is wrapped up in a fictitious dialogue between Poincaré (acting as Einstein's straw man) and Reichenbach. Einstein's Poincaré puts forward the following retort to Reichenbach:

In gaining the real definition [of the rigid body] improved by yourself [by means of differential corrections] you have made use of physical laws, the formulation of which presupposes (in this case) Euclidean geometry. The verification, of which you have spoken, refers, therefore, not merely to geometry but to the entire system of physical laws which constitute its foundation. An examination of geometry by itself is consequently not thinkable. (Einstein [1949] 1970, 677)

Grünbaum has clarified the meaning of Einstein's argument. First we have to remove reference to Euclidean geometry since it merely reflects the predilection of the historical person Poincaré. With this generalization the argument reads: The concept of length already enters into the differential correction laws, namely, into the laws for correcting deformations of the measuring rods that are due to thermic expansion or mechanical stress, and so on. For this reason, the application of the correction laws presupposes that the metric be already known. Conversely, the metric can only come to be known by resorting to these correction laws. After all, differential effects of this sort are construed as deformations and not as veridical indications of spacetime structure. This reciprocal dependence between the metric and differential distortions induces a circularity that vitiates a separate empirical determination of physical geometry. Whatever the ev-
idence may be, it is always possible to cling to one’s pet geometry (see Grünbaum 1960, 80; [1963] 1973, 131–35).

As can be gathered from the passage quoted, Einstein takes his argument as supporting the thesis that geometry is not testable in isolation but only within the context of additional physical laws. Only the combined system of geometry and physics can be confronted with experience. Einstein is, however, not in the least worried about such test restrictions, “Why do the individual concepts which occur in a theory require any specific justification anyway, if they are only indispensable within the framework of the logical structure of the theory, and the theory only in its entirety validates itself?” (Einstein [1949] 1970, 678). A separate test of geometry is as impossible as it is unnecessary.

I should emphasize (pace Grünbaum) that Einstein’s argument does not simply come down to stressing Duhem’s conventionality thesis. The latter concerns the methodological intertwining of hypotheses that are logically independent of each other. This means, in order to test a hypothesis $H_I$, it is necessary to take recourse to some ancillary hypotheses $H_A$; but testing these $H_A$’s does not necessarily presuppose $H_I$. Einstein’s argument, by contrast, envisages a situation in which testing $H_I$ requires reference to $H_2$, and testing $H_2$ necessitates recourse to $H_1$. So we have all the marks of a full-blown circularity that is exactly parallel to the one elaborated by Reichenbach. What Einstein points to here is a differential analogue to Reichenbach-conventionality. And this means geometry remains conventional even after Reichenbach’s rule has been applied.

Einstein’s Circularity Argument Transferred to Particle Trajectories and Light Rays

Einstein develops his argument with exclusive reference to rigid rods and the problems associated with ascertaining rigidity. This procedure does not, however, constitute the only means for measuring metric relations. On the contrary, in the course of the last two decades it has become far more common to regard the use of particle trajectories and light rays as the theoretically privileged method for that purpose.

The most ingenious implementation of this approach was developed by Ehlers et al. (1972). They proceed roughly as follows: First, coordinate systems are introduced so as to allow light rays and par-
ticle trajectories to be tracked. For that purpose, so-called radar coordinates are employed. That is, a spacetime event, such as the spatiotemporal location of a particle, is characterized by sending off a light signal from each of two neighboring world-lines and by recording its emission time and the arrival time of the signal reflected at the event under consideration. "Time" is to be understood here as a nonmetric or order concept, that is, it is only required that the clock run continually and smoothly. Second, the propagation of light is used to attach a light cone, or null cone, to each of the spacetime points under consideration. The null-cone structure thus obtained allows for distinguishing between spacelike and timelike 4-directions, and it can be shown that in this structure the metric is determined up to a positive function of the 4-positions. In the third step the motions of freely falling particles are taken into consideration. These motions determine the straightest lines possible, that is, the timelike geodesics of the respective spacetime. Both results are linked by a compatibility postulate to the effect that these geodesics always remain timelike from the perspective of the null-cone structure. In this way the metric can be ascertained unambiguously.\(^3\)

In this approach the metric is constructed from the paths of free particles and light rays. So one may ask whether Einstein's problem can be solved by doing away with rods and resorting to paths instead. After all, neither the problem of thermic corrections nor of mechanical stresses plays any role in this approach. In fact, however, the trouble reappears at a different level. In order to recognize the analogy to Einstein's problem, we must introduce differential distortions into the Ehlers et al. scenario; that is, we must suspend the condition that our test particles move freely. A relevant differential distortion is electric charge. If the particles used for probing spacetime structure are charged, the influence of possibly present electromagnetic fields on their trajectories has to be evaluated and (as the case may be) corrected. Such corrections can be carried out by applying Lorentz's force law.

The problem with that procedure is that in the generally covariant formulation of that law the metric appears:

\[
f^a = qg^{ab}F_{bc}(dx^c/dt)
\]

(with \(f^a\) denoting the correcting Lorentz force, and \(F_{bc}\) the electromagnetic field strength tensor, see Weinberg 1972, 125). As can be
gathered from this equation, a reciprocal dependence exists between the metric $g^{ab}$ to be determined and the correcting electromagnetic force $f^a$. Calculating this force from Lorentz's law requires knowledge of the metric, and conversely, the metric can in general only be determined by applying this force law and thereby coping with differential trajectory deformations. This situation thus apparently leads into a circle that parallels the one in Einstein's rod scenario: In order to reliably measure the metric, we have to carry out corrections that, in turn, make use of the metric. This means that, from the perspective of the trajectory method, distortions induced by lack of neutrality are in fact self-referential. Correspondingly, Einstein's differential analogue to Reichenbach-conventionality has a general bearing on spacetime measurements.

Grünlbaum: Dissolving Einstein's Circularity by Way of Successive Approximations

In the remainder of this essay, I discuss the import of Einstein's circularity argument on the measurability of physical geometry. Mutual dependence of the sort described by Einstein inevitably creates the impression that a vicious circularity is present. In that event, one of the relevant quantities (the metric tensor, for example) would have to be chosen arbitrarily and the other one (electromagnetic force, for instance) would have to be correspondingly adjusted. After all, this is to be done in Reichenbach's universal-force scenario. In fact, however, reciprocal dependence does not necessarily entail circularity. We have two possible ways out of the difficulty, namely, the method of successive approximations and the selection of undistorted instances. The first procedure attacks the problem head-on and the second one circumvents it. Each method can be applied to the original rod-variant of the argument, for one, and to its updated trajectory-version, for another. This leaves us with a total of four options for coping with Einstein's argument. I will now address each of these options in turn.

We owe to Grünlbaum an elaboration of the application of the method of successive approximations to the rod-variant. He considers a situation in which only thermic distortions are present. In that case one starts with an arbitrary geometry in the correction law for thermic expansion and determines the geometry with the help of rods
corrected by this law. The geometry obtained does not in general co-
incide with the one employed in the correction. So one uses this mea-
sured geometry for effecting the correction a second time and applies
again the rods corrected in this improved fashion to determine the
prevailing metric relations. This procedure is to be repeated until an
agreement is reached between the geometry that enters into the cor-
rection law and the geometry that is obtained by measurements with

If this procedure indeed converges to a result that is independent of
the geometry used at the start, it is sensible to identify this resulting
geometry with the geometry of spacetime. The problem is, however,
that there are lots of circumstances under which this procedure is not
convergent. A necessary precondition for convergence is, first, that
curvature is spatiotemporally constant. That is, in order for the
method to work successfully, the curvature of the region under scru-
tiny must be neither time- nor position-dependent (Grünbaum is well
aware of this limitation, see Grünbaum [1963] 1973, 146). As a mat-
ter of fact, however, this is not generally true in our universe. The
general theory of relativity associates spatiotemporal curvature vari-
ations with a large number of gravitational effects.

Second, the reliability of this method presupposes that the distor-
ting temperature variations remain unchanged during its application.
Clearly, if the strength of the perturbing influence changes in the
course of the correction process, we cannot expect to obtain a con-
vergent series of results. Hence, this approach relies on the condition
that there is a stable spatial pattern of distortions. Only on that con-
dition can this pattern be extracted from successive measurements.

Third, the rods used in performing the measurements must be
guaranteed to be perfectly elastic. It is requisite that the possibly
changing intensity of the deforming influences be faithfully reflected
in corresponding changes in the length of the rods. This requirement
is violated if a "hysteresis" occurs due to inelastic deformations. In
that case the rod does not regain its original length after the distort-
ing influence has ceased but rather retains a somewhat altered length.
Consequently, the rod would indicate the presence of a distortion
where in fact none exists. The problem here is that judging whether
the condition of perfect elasticity is met demands recourse to reliable
length measurements which in turn were supposed to be established
by the whole procedure.
These three restrictions make Grünbaum’s proposal unsuitable as a
general means for disentangling differential distortions and geometric
effects. His ingenious application of the method of successive approximations to rigid rods, useful as it is in some cases, is not
generally applicable.

I should point out, however, that the limitation to the exclusive
presence of temperature variations is inessential. Grünbaum’s method
is successful even when several differential distortions occur simul-
taneously. Suppose that in addition to temperature variations a
(constant) mechanical deformation is present. Such deformations are
governed by Hooke’s law, and from that it appears that the evalua-
tion of the distorting force necessarily makes use of length measure-
ments. So we encounter again a circle analogous to that involved in
thermic corrections. In this case, however, we can provisionally as-
sume a geometry, carry out all relevant corrections unambiguously,
and measure the resulting geometric relations. Because all possibly
occurring deformations can be evaluated on the basis of a posited
geometry, we can effectively carry through the successive approxi-
mation procedure. The simultaneous presence of several differential
distortions leads to only technical rather than fundamental
complications.

Furthermore, the viability of Grünbaum’s proposal remains unaf-
fected by an epistemological objection of the following kind: The
method of successive approximations works satisfactorily only if we
know in advance which distortions are present and, correspondingly,
which correction laws are to be applied. In particular, there may oc-
cur hitherto unknown perturbations that consequently escape our
corrective procedure. But the nature of the distorting influences can-
not be established by means of the experimental set-up under consid-
eration. The reliability of this approach thus crucially depends on
conditions whose validity cannot be verified within its framework.

This objection does indeed hold, but is irrelevant in the present
context. It would only apply to a situation in which we wished to use
Grünbaum’s method to determine the prevailing geometric relations
from scratch. That is, it refers to a situation in which we are only
given some possibly distorted length measurements and are asked to
disentangle geometric and differential effects. In that situation Grün-
baum’s method clearly fails. But this problem is distinct from the one
created by Einstein’s argument. The latter proceeds on the assump-
tion that the relevant distorting influences are known and denies that even under these circumstances the metric relations can be unambiguously determined. Einstein’s argument has nothing to do with the difficulty of ascertaining what kinds of distortions are present but rather with the problem of quantitatively evaluating their impact on length measurements. Even if we know what kinds of perturbations spoil our measurements, the ensuing correction circularity prevents us from unambiguously sifting out the disturbing effects. So neither Einstein’s problem nor Grünbaum’s proposal to its solution is affected by the epistemological difficulty sketched.

The conclusion is that Grünbaum’s implementation of the first option is helpful in some special cases of Einstein’s problem, but it does not provide a means for its general solution.

Successive Approximation Applied to the Trajectory Case

Virtually the same conclusion emerges from the application of the method of successive approximation to the trajectory case. At first, to be sure, that method appears to break down right at the start. In order to see this let us once again consider Lorentz’s force law. In addition to the previously mentioned reciprocal dependence between \( f^a \) and \( g^{ab} \), there appears another reciprocal dependence in that law. The charge \( q \) enters into the calculation of the correcting force, and this charge can in general only be determined by recourse to electromagnetic fields, that is, by recourse to Lorentz’s force law. Charge relates the field strength to the force and this implies that we need the value of the charge to calculate the value of the force. Conversely, the value of the charge can in general only come to be known by the force exerted on that charge in an electromagnetic field. So there is a reciprocal dependence between \( q \) and \( f^a \) in addition. Because of this double reciprocity, the application of the method of successive approximation is blocked. There is too much free play for the quantities involved.

But there exists a remedy for this difficulty. For the moment let us restrict our attention to just one particle. In that case we may assume that—barring collision processes—it retains its charge value so that the charge dependence of the force need not be taken into account. Then we start an adaptation procedure between geometry and force. That is, we posit a geometric structure and explore on that basis
the motion of a particle of unknown (but constant) charge. This is done by calculating the particle acceleration, that is, the deviation of the observed particle trajectory from the posited geodesics, and by trying to account for that acceleration by introducing appropriate \( F_{bc} \)-functions. Next we take another particle of likewise unknown but constant charge and examine whether its motion can be accommodated as well by the formerly assumed geometric and field structure. This trial-and-error procedure is repeated until the acceleration values can be explained by ascribing a parameter to each particle that does not in fact change spatiotemporally. This set of parameters may then legitimately be identified with the respective particles' charge values.

This approach tries to avoid the previously mentioned double reciprocity problem by considering a series of experiments in which the critical charge parameter can be considered fixed and by applying the condition that the theoretical entities "geometry" and "field" be adjusted such that the ensuing charge ratios of any two particles indeed come out as spatiotemporally invariant. Systematically speaking, we take advantage of a constraint imposed on charge by electromagnetic theory: Charge is a property inherent to a particle which consequently remains unaltered unless the nature of the particle is changed. By virtue of this constraint, the circularity threatening the applicability of the method of successive approximation does not occur. It is clear, on the other hand, that this constraint must be presupposed for that method to work and thus cannot be tested empirically. If unaccounted charge fluctuations occur, we are heading right into a mess. Either we obtain no consistent set of charge parameters or an inaccurate one. But since our problem is not the determination of the prevailing geometry from scratch, this untestability objection does not carry much weight. We are allowed to avail ourselves of the pertinent theoretical apparatus.

This procedure suffers from a more serious shortcoming, however. Another constancy assumption is involved: Neither the geometry nor the field is allowed to change in time. If there are any fluctuations of either quantity while the procedure is carried out, the results obtained are clearly mistaken. And again, the validity of this constancy assumption has to be presupposed and cannot be tested. What makes this assumption appear much more problematical than its charge analogue is that, in contrast to the latter case, it is by no means guaranteed theoretically that the geometry and the field retain their val-
ues. This constancy is a contingent feature of the particular situation under consideration and not a (supposedly) general trait of nature.

Hence the conclusion is that we are not better off now than we were before. The method of successive approximation offers a basis for tackling special cases of the differential circularity problem, but it fails to bring us closer to its general solution. Accordingly, Einstein's problem cannot be overcome in a general fashion by relying on this method.

Grünaum Again: The Selection of Undistorted Rods

If distortions cannot be adequately treated, they can perhaps be discounted. So let us turn to the second type of options, that is, to the selection of ideal cases. The rod variant of this option has again been studied in detail by Grünaum. In order for that method to work noncircularly, it is necessary to identify undistorted cases without having a metric at our disposal. For the rod scenario this amounts to empirically securing the absence of differential deformations without availing ourselves of metric relations. Under such circumstances we cannot uniquely compare lengths numerically on the same world-line (i.e., we cannot give length ratios), and we can in no way compare lengths on different world-lines. What we can do, however, is to judge whether or not a rod has the same length as another one placed next to it in the same direction. Local congruence can be established nonmetrically. And this capacity suffices for ascertaining the absence of perturbations. If any two rods of different chemical composition that coincide locally always remain locally congruent when being jointly transported to different locations, this reliably indicates that the region under consideration is perturbation-free (see Grünaum [1963] 1973, 136).

In that event it is safe to conclude that the geometric relations obtained truthfully indicate the spacetime structure. But cheers are premature. A serious limitation of this method is due to the possible presence of tidal forces. A curved spacetime induces relative accelerations (and consequently deformations) in a particle ensemble. In the case of an extended rod this amounts to a substance-unspecific force that tends to deform the rod and to alter its length. But since the actual deformation of the rod is the joint effect of the tidal force and the substance-specific force of cohesion, this resulting deformation de-
pends on the material employed. As a result of the different elasticity of different materials, changing tidal forces may induce responses of different strength in different materials. This implies that chemically distinct rods may not remain locally congruent under transport because curvature variations occur, despite the fact that the region under consideration is perturbation-free.

Consequently, Grünbaum's perturbation test may be falsely positive. The test is not only sensitive to differential distortions but also to changing curvature (or changing tidal forces). It may indicate the presence of differential distortions where there are in fact none. Grünbaum's test is indeed sufficient to ascertain that a certain region is perturbation-free (namely, if local congruence is retained). The reverse, however, does not hold. One cannot reliably detect the presence of perturbations, and one cannot make sure, consequently, that all perturbation-free regions are correctly identified.\(^4\)

A second limitation is involved in Grünbaum's approach. Suppose that the perturbation test is rightly positive and let us ask what can be derived from that result. The answer is: precisely nothing. More specifically, we cannot extract the prevailing geometry from distorted cases. That is, we cannot derive the geometry present in distorted situations from the geometry realized in the undistorted ones. Such a derivation would require a comparison between the distorted and an undistorted region, and in that case we can never rule out that the geometry is actually different in both regions. So the transition from a perturbation-free state of affairs to a distorted one is blocked here. Clearly, however, differential distortions are almost ubiquitous in our universe. Accordingly, the selection of pure instances, when applied to the rod scenario, is of only limited help.

**Selection of Pure Instances in the Trajectory Case**

Our last resort is to apply the selection method to the trajectory scenario. Our task is, then, to identify free-particle trajectories without relying on metric procedures. If we follow Reichenbach's recommendation and set universal forces equal to zero, a particle is free if its path is at most influenced by gravitational effects. In that case its trajectory is a geodesic. So our task comes down to nonmetrically identifying geodesics. If this can be accomplished, deviations from the geodesic path are to be attributed to the presence of differential
distortions. And by this means the latter could be evaluated and consequentely corrected.

A generally applicable test exists for singling out geodesics nonmetrically. So now the cheers are in order. A geodesic can be characterized by three conditions. It is, first, timelike and, second, unique in the sense that the entire trajectory is uniquely determined by specifying the 4-direction of the trajectory at one point on it. This condition is obvious in the special case of a straight line in flat spacetime, and the just-given form is a natural generalization of that special case to situations with nonvanishing curvature. These two conditions, however, are not only satisfied by geodesic motions but also by particle motions under the influence of electromagnetic fields. So the third condition must carry the bulk of the weight. This condition invokes a local microsymmetry of geodesics that can be characterized roughly and intuitively as follows. Consider a collection of path elements or curves that are all passing through a given event. Disregard, moreover, the special parametrizations of these path elements or, put the other way around, construe every path element as an equivalence class of differently parametrized curves. Then introduce a "dilation operation" that radially stretches or contracts the path elements away from or toward the event under consideration. If this operation leaves the paths invariant, that is, if it amounts to a map of each path onto itself, these paths are geodesics. After all, it is intuitively clear that the only paths that are left unchanged by such a dilation procedure are radial straight lines, and it can be shown that the same feature is present in their analogues in nonflat geometries, namely, geodesics. A microsymmetry of that sort is sufficient to single out geodesics in every spacetime manifold (see Ehlers 1988, 155–56; Ehlers and Köhler 1977, 2014, 2017). Trajectories of small gravitational monopoles indeed pass this geodesics test.

Now we are almost done. The last step only consists in realizing that what we have here is an effective criterion for the absence of differential distortions. This implies that we are now in a position to reliably set apart the motions of neutral and charged particles. Only the former, and not the latter, pass the geodesics test. It is now easily possible to evaluate electromagnetic perturbations. For that purpose we only have to compare the paths of neutral particles to those of charged ones in the same spacetime region. The latter's deviations indicate the intensity of the distortions present which can consequently
be quantified and corrected. Unlike the rod scenario, the comparison between the undistorted and the distorted case can here be effectively carried through.

It deserves emphasis that this procedure is not restricted to electromagnetic distortions. It is not confined to situations in which the nature of all possibly occurring differential distortions is known beforehand. The reason is that the pure state is not identified by a stepwise exclusion of distortions but rather by means of a direct operational criterion. After an empirically applicable criterion for geodesics is at hand, we can simply count every particle whose motion deviates—whatever the cause may be—from the thus distinguished paths as distorted. In order to carry out this procedure we need not know in which way its motion is distorted.

Conclusion

This leads to the overall conclusion that there is indeed a separate access to physical geometry. The latter can be obtained, even in distorted cases, without making use of additional physical correction laws. That is, pure instances can be selected or self-referential distortions can be avoided without loss of generality. This works because we can arrange things such that the perturbing influences have no effects. Neutral (small, spinless, and so on) gravitational monopoles follow unflustered their geodesic paths, regardless of all turmoil on the differential level. This peculiarity has no analogue in the rod case and this is why the latter method is of no general avail.

This conclusion implies that Reichenbach and Grünbaum are right and that Einstein is wrong. Physical geometry can be established and tested in isolation from the differential correction laws so that the geometry is uniquely determined after a decision about universal forces has been made. On the other hand, Reichenbach and Grünbaum are only right for contingent reasons. That is, a separate access to geometry is in general only possible because undistorted motions do in fact exist. If, for instance, there were only charged particles, no general solution to Einstein’s differential circularity problem could be given. Fortunately enough, nature does not hide its pure states entirely.

This discussion neither constitutes an argument for the nonconventionality of geometry nor for an antiholistic or non-Duhemian interpretation of geometry. As to the first item, the present argument
clearly does not extend to universal forces so that Reichenbach’s conventionality thesis remains untouched. The result is only that the decision to regard gravitationally influenced particle motions as free can be unambiguously put into experimental practice. Second, this is at the same time one of the reasons why Duhem’s thesis is unscathed by the present argumentation. We are always free to introduce universal forces and thus to create a conceptually distinct but empirically equivalent description. The line of demarcation between geometry and physical force can be shifted at will. Moreover, the foregoing discussion does not imply any restrictions as to the structure of the differential correction laws themselves. How differential distortions are to be accommodated theoretically, that is, what kinds of distortions are to be assumed and by what laws they are supposed to be governed, is left open. So there is still enough room for theoretical holism. The upshot merely is that we cannot tamper with differential distortions in order to hold fast to our favorite geometry. So one special option to uphold one special element of a conceptual structure is blocked. And this is certainly not enough antiholism to bother even the staunchest Duhemian.

It appears, then, that the overall thrust of the argumentation as well as the results arrived at match with Grünbaum’s approach. Although the details of the argument and the interpretation of the results are not always coincident, there is perfect agreement with the general conclusions reached by Grünbaum almost three decades ago. This is all the more remarkable since a lot of new developments have meanwhile occurred in spacetime philosophy. We may thus conclude that Adolf Grünbaum’s work has stood the test of time.

NOTES

I would like to thank my colleague Claus Lämmerzahl for advice in matters of physics.

1. Reichenbach’s recommendation refers to 4-forces, not to 3-forces such as the Newtonian gravitational force. For the relation of both quantities see Earman and Friedman (1973, 355). For brevity’s sake I will omit such physical complexities.

3. In fact, the metric is still not completely fixed. An ambiguity remains that is due to the possible presence of second clock effects. (I will not dwell on that problem here. For a more detailed discussion of this approach, see Carrier 1990).

4. Millman argues that Grünbaum’s test is not even sufficient for establishing freedom from perturbation, but his argument is less than persuasive. He imagines a situation in which rods of different chemical composition respond in an equal fashion to a differential force. In that case the perturbation test would be falsely negative (see Millman 1990, 29–30). The trouble with this argument is that it is either irrelevant or incoherent. If it is supposed to refer to a situation in which all actually employed (but by no means all existing) materials show an equal response, the failure to detect the differential distortion is simply due to the use of a biased sample and thus eventually due to inductive uncertainty. But Grünbaum does not purport to resolve the latter. If, on the other hand, Millman’s argument is to refer to a situation in which all existing materials respond likewise, we no longer deal with a differential force. The same reply holds with respect to a conspiracy version of that argument: The superposition of several differential forces brings about a substance-independent deformation (see ibid., 31). But either there exist situations in which these conspiring forces can be empirically disentangled or we are not dealing with differential forces at all.

REFERENCES


