BELL'S 'LORENTZIAN PEDAGOGY': A BAD EDUCATION

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Bell's 'Lorentzian Pedagogy' has been extolled as a constructive account of the relativistic contraction of moving rods. Bell claimed advantages for teaching relativity through the older approach of Lorentz, Fitzgerald and Larmor. However, he describes the differences between their absolutist approach and the relativistic one as philosophical, and claims that the facts of physics do not force us to choose between them. Bell's interpretation of the *physics* of motion contraction, and therefore of constructivist as opposed to principle approaches, is indeterminate. His flawed pedagogy never directly addresses the difference between Fitzgerald and Lorentz contractions.

1 Introduction

Merely that J. S. Bell wrote 'How to teach Special Relativity' (1987) ensures its interest as a text; further, it is the icon of a Constructivist approach to understanding relativity (Brown & Pooley 2001, 2003; Brown 2005). I discuss only Bell's paper, not Constructivism generally. I show that its intentions and conclusions are seriously obscure.

Constructivism is debated elsewhere (see e.g. Balashov & Janssen (2003), Janssen (1995) Norton (2007); Janssen (2009) Nerlich (2008)).[1] A remark of Brown's makes clear what the Bell-inspired issues are thought to be and why they are supposed fundamental:

… a moving rod contracts and a moving clock dilates *because of how it is made up and not because of the nature of its spatio-temporal environment.* Bell was surely right.

(Brown 2005 p. 8, his italics)

2 A problem of interpretation

There is no obvious charitable interpretation of Bell's paper: simply compare its first page with its last. Both pages concern how to teach special relativity but the lessons described on the two pages differ sharply.

The first page tells a strong story. Bell's teachings would 'emphasize the continuity with earlier ideas' and play down the 'radical break' of special relativity. The radical break may 'destroy completely the confidence of the student in perfectly sound and *useful* concepts *already acquired'* (67 my emphasis – presumably, acquired before an education in relativity). Most of the paper is about the contraction of moving rods. Throughout, Bell uses the phrase '*Fitzgerald* contraction'[2]; 'Lorenz contraction' never occurs.

Bell is seldom explicit; he says little about what the *Fitzgerald* contraction is, nothing about the radical break; a Lorentz contraction is not described or contrasted with *Fitzgerald's*. 'Earlier ideas, perfectly sound' surely means an intrinsic contraction. Bell does not say so.

The last page says nothing like this. Lorentz and Einstein differ, in "two major ways. There is a difference of philosophy and a difference of style … the facts of physics do not oblige us to accept the one philosophy rather than the other … the special merit [of the Lorentzian pedagogy] is to drive home the lesson that the laws of physics in any *one* reference frame account for all physical phenomena, including the observations of moving observers. … There is no intention here to make any reservation whatever about the power and precision of Einstein's approach. But *in my opinion there is also something to be said* [my italics] for taking students along the road made by Fitzgerald, Larmor, Lorentz and Poincaré. The longer road sometimes gives more familiarity with the country." The last three sentences are so modest, so anodyne that, surely, no one would be interested in disagreeing with them. There is nothing here about the rescue of concepts already acquired.

It is clear what Bell wants: a contraction that is real in being intrinsic and caused. He wants to avoid its necessary condition: the Lorentzian aether or a preferred frame. Thus the paper lacks commitment to any relata for motion, relative or absolute.

3 Lorentz, Einstein and the *Fitzgerald* contraction

(a) On the face of it

On the face of it, Lorentz and others make factual claims about physics: there is a luminiferous aether; the rod's contraction is intrinsic, caused by motion through it, as described by Maxwell's equations. The sentence "A moving rod contracts" is semantically like "A cooling rod contracts": i.e. no reference to another relatum is implied. [3]

On the face of it, still, Einstein dissents, countering with different claims about the facts of physics: there is neither an aether nor an absolute motion to cause the contraction; it is not intrinsic, but a relation between a thing and an inertial frame of reference. If that first-face comparison is correct, then Lorentz and Einstein do differ over physical facts; the difference obliges us to choose between them for the purposes of physics.

Bell gives no argument for rejecting these views. He simply states another: their differences are philosophical. Philosophically, "Einstein *declares* [my italics] the notions 'really resting' and 'really moving' meaningless … only the relative motion … is real". Lorentz "… *preferred* [my italics] the view that there is indeed a state of *real* [Bell's italics] rest defined by the 'aether'…" (77). Einstein sounds arbitrary and peremptory, Lorentz arbitrary and whimsical. Bell does not choose between them.

No reason is given for regarding Lorentz's view as mere preference. Yet it is central to a causal interpretation and no whim. In his 1905, Einstein did not declare anything meaningless; he showed that the introduction of an aether "will prove to be superfluous" (p. 38). Bell's claim that the theory of relativity arose from "experimental failure to detect any change in the apparent laws of physics in terrestrial laboratories…" (77) is inaccurate (Einstein 1920). It arose principally from a problem in Maxwell's electrodynamics (see the first paragraph of Einstein's 1905 paper, discussed below). Einstein clearly thought 'real motion' unsatisfactory in *any* theory and avoidable in relativity.

(b) Philosophy or physics?

We are left to conjecture what Bell's 'philosophical' means.[4] Einstein showed an aether superfluous by constructing a usable theory of electrodynamics without it: that is not philosophical. Lorentz's theory poses the epistemological difficulty that the aether is an undetectable relatum for motion: aether velocities and *Fitzgerald* contractions remain unknowables. They are not useful concepts. But their intended semantics is definite. Things move *through the aether*. Not so for Bell. He consigns the relatum of motion to the ragbag of pointless questions – philosophy. He commits to no relatum for motion. The result is not merely that we can't *know* what is moving and what not: nothing counts in Bell's scheme as rest or motion. That is undefined, uninterpreted. A "velocity" vector **v** is purely an ordered set of numbers. It engages with the mathematics of Maxwell's equations but not with its physics. We are worse off than with Lorentzian unknowables: Bell's concepts are physically meaningless because incomplete. His **v** merely looks like a velocity. [5]

Contraction is a function of velocity, but velocity is undefined. Here is the key weakness of this paper. Further, this indeterminacy also places under a "philosophical" cloud, any property not Lorentz invariant. That directly means that the 'contraction of a moving rod' itself is placed among matters on which the facts of physics do not require choices. The undertaking of Bell's opening page fails.

Conceivably Bell was hinting at the view that simultaneity, hence measurement of length of anything moving, is a mere convention, and no fact of physics. That is familiar to philosophers but there is no hint of it in Bell. The suggestion is implausible.

(b) Derivation from Maxwell's Equations

Bell offers 'a simplified version of the Larmor-Lorentz-Poincaré approach' to calculate the *Fitzgerald* contraction (68-74) from Maxwell's equations 'without mystification' (68)[6]. It is sketched in the context of the classical atom and electron. When a point charge is set in rapid motion its spherical Coulomb field contracts, roughly speaking, in the direction of motion. '…this distortion of the field of fast particles will alter the internal equilibrium…a body set in rapid motion will change shape [which is] the *Fitzgerald* contraction' (69).

At this point, the Lorentz-educated student, having perfectly sound and useful concepts, should ask why the field contracts. Historically, a reason was given − the charge is moving through the aether. (Lorentz et al 1923 §I, II; e.g. p. 11). Bell fogs this; how his calculation exemplifies the Lorenz approach is obscure. The contraction languishes as an uncaused mystery. The 'approach' is set in 7 pages of prose and calculation; nearly all of it could be read as a relativistic single frame-account, tacit as to which frame. Nothing tells us decisively that the field contraction is not relativistic, just as the contraction of the rod itself would be. At the end of it, Bell does write as if the motion is real, i.e. absolute. (75-6). He does not say how, and his calculation and explanation ignore how. The only non-relativistic, non-aetherial explanation for the contraction of the Coulomb field is *motion through absolute space* - a notorious mystery.

Finally, Bell writes (76) 'Can we conclude then that an arbitrary system, set in motion, will show precisely the Fitzgerald and Larmor effects? Not quite'[7]. But not at all! What it is to "set in motion" an *arbitrary* system is undefined: e.g. does it accelerate or decelerate through an aether? We can't conclude that it is contracted rather than expanded. The counterpart, in relativity, is that an accelerating rod may contract with respect to one frame, expand with respect to another.[8]

Given a body in an inertial state, then it is contracted relative to every frame in which it moves. But, given a *non*-inertial body, it fails to accelerate and contract with respect to infinitely many of the frames in which it is not at rest. It decelerates and expands.

Bell's Lorentzian concepts seem perfectly sound and useful only by ignoring their indeterminacy. They are not *soundly* causal. We can never *use* them in any particular case.

(c) The 'special merit'

The adequacy of a single frame in special relativity is beyond question. Students should be taught the full frame-relative story of contraction. However, since Lorentzians don't recognise frames of reference, they can't change them. The adequacy of a single frame as a *relativity* lesson is unlearnable in that pedagogy.

Bell stresses (twice in italics on 72; again on 75) the fact that, in a single frame account, the observations of other observers can be deduced and explained. This is a commonplace of relativity.

Bell writes 'The longer road sometimes gives more familiarity with the country' (77). Nothing in relativity blocks longer roads; they may be taken with respect to any frame whatever. Following many roads through the country suggests even greater familiarity with it. As Bell says 'The laws of physics in *any* one frame account for all physical phenomena'. (77; my change of emphasis). We need delete only the Lorentzian view that there is just one, uniquely *right,* road.

A reservation must be made about the 'special merit'. Different frames of reference provide *different* complete accounts of the physical world. The frame-description is unlike a perspective in being complete, yet like it in being slanted. Bell neglects the slant. How well a student will grasp a relativity theory if she is weakly grounded in changes of frame is doubtful.

(d) Difference of style

As to style, Bell says "The difference of style is that *instead of inferring the experience of moving observers from the known and conjectured laws of physics*, Einstein starts from the *hypothesis* that the laws will look the same to all observers in uniform motion." (77; my italics. The claim, repeated in Brown and Pooley 2006, p.262, is false. The hypothesis is Einstein's first postulate, but not how he started. In 1905 he began by inferring the experience of moving (and rest) observers from the known and conjectured laws of physics. The first sentence of the 1905 paper notes that 'Maxwell's electrodynamics – as usually understood at the present time – when applied to moving bodies leads to asymmetries which do not appear to be inherent in the phenomena' (Lorentz et.al. 1923, 37.). Pairs of conclusions drawn by differently moving observers are found paradoxical; e.g. an encounter between a magnet and a conducting coil is different depending on whether the magnet moves inside the coil, or the coil moves to enclose the magnet. The 1905 paper begins, not with the invariance of laws, but with oddly different consequences for still or moving observers.

To simplify (as in Norton): consider a magnet fixed inside a coil with free charges in it. To an observer for whom the apparatus is at rest, there is no current in the conductor. For a fast passer-by, there are two, mutually cancelling, currents, equal and in opposite directions. One is produced by the induced electric field, the other by the motion of the charges in the magnetic field. Neither observer measures a current.

No coil both has two cancelling currents in it yet no current at all. On the face of it, the coil is just a familiar physical object. But these results cannot both be true of one and the same *familiar object*. Either, at least one of the observer's claims is false but nothing can tell us which one (Lorentzian pedagogy); or the description is relativistic, and so not directly about a familiar physical thing but about a thing-in-a-frame (relativity). Phrases such as 'the rod', 'the conductor' are referentially ambiguous in relativity theory.

First, relative to different frames, different *components* of the same electromagnetic tensor-field are in play. So the currents in one frame may vanish, as mere x_i-components, of the rod-in-that-frame. When the frame is changed from F_i to F_j (assuming a standard configuration) the new, x_j-components differ without change in the condition in spacetime that the tensor describes. Second, there is no frame-transcending 3-dimensional object (e.g. a coil) common to both frames. There is no frame-transcending dynamical (causal) description or explanation of the contraction of one and the same entity – "rod" is frame-ambiguous referentially: that is the price of consistency. We miss this if we confine our discussion to a single frame.

4 What is a relativistic rod?

Operations measuring the length of a rod-moving-in-a-frame shed some light on why phrases like 'the coil' and 'the rod' are referentially ambiguous in relativity theory. Yet they neither define nor make explicit the entity measured. Coils are not basic entities. What things are?

This is a basic problem of 1905, preceding Minkowski's conception of spacetime. Einstein's first paragraph presupposes an answer, but does not give it. Only referring phrases like 'the rod in frame F_i' (to return to the main example) can pick out things to which we can consistently ascribe electromagnetic states.

Consistency in syntax is easy: Lorentz covariant properties must not be ascribed to a rod but only to a rod-in-a-frame; if a frame is contextually presupposed, 'the rod' may refer uniquely. That roughly describes common practice. But the underlying semantics is less straightforward.

In Minkowski spacetime a referent of 'rod' is a 3-dimensional continuant entity composed of a time-extended continuum of parallel spacelike sections of a 4 dimensional object – the 3-rod and the 4-rod, as one says. A single section of a 4-rod is *slanted* in a way that depends on the frame: it may be *time-orthogonally* slanted if at rest in one frame, but not thus slanted in any frame moving relative to the first. Let 'Excalibur' rigidly designate my 3-rod: then Excalibur-in-F_i is not identical with Excalibur-in-F_j, despite unique ownership, since the 3-rods are composed of distinct spacelike sections of the 4-rod. The two are distinct since their slanted spacelike-sections are distinct. But this springs not only from differences of frame but also differences of velocity within a frame. This is hardly surprising since frames differ only in uniform velocities. It is not common syntactic practice to distinguish Excalibur at rest from Excalibur in motion within a presupposed frame. Yet the semantic criterion that makes Excalibur-in-F_i distinct from Excalibur-in-F_j applies equally in distinguishing Excalibur-at-**v**-in-F_i from Excalibur-at-**u**-in-F_i.. (Petkov 2002, §3.)

Bell's Lorentzian pedagogy, confining itself to one frame, ignores slant and thereby the distinct referents that ambiguate reference of the phrase 'the rod'. Its lessons risk leaving students naïve as to what the explanation is about – familiar rods or relativistic 3-rods - and whether it is a causal explanation. To return to the coil; there is no illusion or subjectivity but mere relativity. The coil-in-F_i-at-**0** really has no current in it and the field components of the electromagnetic tensor in the rest frame reflect that. The coil-in-F_j-at-**v** really has two cancelling currents, also as described by the components of the field in the frame. The absence of a frame-transcending cause of this relative difference is no mystery. The entities are different.

Bell evades commitment to an intrinsic contraction; he is silent whether it needs Fitzgerald's context of the aether or whether it is meaningful within relativity. Yet a *Fitzgerald* contraction is intrinsic and caused; like cold contraction, it is a property of a rod. That implies some absolute rest state, in which no rod's intrinsic length is contracted or expanded by a motion.

The 'contraction of a moving rod' under Lorentz transformation is something quite different. There is no change in an entity basic for relativity. There are distinct frame-artefactual entities, defined by distinct components, differing with 'slant'. Relativity is inconsistent if this is ignored.

So Bell's detailed story is irrelevant to a grasp of contraction. Any interpretive problem about contracted rods also arises with the contraction of the fields of the charges making up the rod: it's the same contraction. Going from rod to electron is going nowhere relevant.

Nevertheless the relativistic story of the rod (rod-in-frame-at-**v**) must be open to testing that all field laws are Lorentz invariant, and, therefore, it is open to falsification. That concerns the truth, not the content of the theory. In relativity, what counts is how the spacelike sections of 4 dimensional things are slanted, not what pulls the ends together from within.

Einstein's reservation as to relativity as a principle, not a constructive theory deserves comment here. He contrasted thermodynamics with the kinetic theory of gases, only the latter being an explanatory constructive theory (Brown and Pooley 2001 §3). In an isolated macro thermodynamical system, entropy increases. But kinetic theory permits decreases in many micro sub-systems over the same brief period. Generally, entropic states of micro subsystems don't mirror those of containing macro ones. The relativistic contraction of a moving rod, however, *entails* a precise match at micro and macro levels, asserting that Lorentz covariance rules all relevant field theories. We know little about the complex electromagnetic tensor fields that make up a rod and differentiate a rubber rod from a wooden or a steel one. But relativity says this: a moving rod, however it is constituted, is contracted in the direction of its motion by a known factor; a moving tensor field, however complex, is equally contracted (i.e. the tensor components of each electron field change) by the same factor in the direction of its motion. The one contraction does not cause the other. They are not merely equal, they are the *same* contraction: the rod's motion-contraction is just the sum of the contractions of its every part, and vice versa. In all cases, at all scales, components differ with frame. The 'principle' story and the 'constructive' story are identical in the relevant respects, despite the greater, largely unknown, detail and complexity of the latter story.[9]

5 Accelerations and breaking threads

Bell considers the contraction of an accelerating rod; with respect either to a frame or to the ether, something happens to *it*. An active boost, caused by a force, changes its velocity and length. No mere redescription from different frames captures this.

To illustrate the dire and prevalent effects of poor education, Bell cites an 'old problem' (68) about acceleration, the occasion for an amusing and surprising anecdote. The problem is this: two aligned rockets are joined front to back by a thread taut just short of breaking. The rockets have 'identical acceleration programmes' which are fired simultaneously relative to the rest frame and move the system along the line of the thread. In the CERN canteen, Bell raised the question 'Will the thread break?' A mild furore ensued and was referred to the Theory Division in not very systematic canvass of opinion. It resulted in a clear consensus that the thread would not break. Bell's contrary answer is that the thread 'will become too short because of its need to Fitzgerald contract, and must finally break'. He says (68) that the conclusion is 'perfectly trivial in terms of [the rest frame's] account of things and the Fitzgerald contraction'.

Here are facts of physics on anyone's showing. So it seems.

The moral of the episode does not lie in faulty education in relativity but only in a lamentable readiness, on the part of CERN, to shoot from the hip at vague targets.

First, recall that referential ambiguity dogs Bell's assumption that an accelerated rod retains its identity. It does so only in the context of Lorentz-absolutism. Further, if the firing of the rocket motors *decelerates* the system through the aether, the system expands. Does the thread break? Well, not because of any contraction.

How are contractions functions of accelerations? In the example, the acceleration programs are described only for the rockets, not for the thread. For elastic rockets, the placement of the identical motors is critical for the thread in the first moments. If at the back of each rocket, each will be somewhat crushed by the rear thrust and the back of the front rocket takes off earlier than the front of the back rocket. Unwanted complications occur with other placements. None of this concerns a *Fitzgerald* contraction of the thread. A determinate question about Lorentz contraction presupposes an acceleration for *each point*. This falls within kinematics in the sense that it deals with motions and contractions ignoring dynamics, i.e. accelerating forces. That is not so for the *Fitzgerald* contraction which is explained by dynamical changes in the thread arising from its motion through the aether.

Bell largely treats it as an exercise in kinematics. His second proviso (76; see also §3*(c)* above) on whether acceleration yields the *Fitzgerald* contraction, is that the acceleration must be gentle. That is his only dynamical reservation: it is irrelevant. We need to know in all detail how the thread is accelerated. We don't. What Bell means by 'brutal' acceleration is brutally *different* accelerations for neighbouring points. Acceleration will not tear a nucleus from an atom if the nucleus is accelerated according to the pattern that follows. Forces can be arbitrarily large, so long as each point of the thread is accelerated appropriately. The contraction is a direct function of the acceleration, not of its causes.

Trivially, as Bell says, the thread will snap: two points that are identically accelerated with respect to a frame will keep at the same interval in it at each moment. No matter how it is accelerated, and at any speed, the thread contracts relative to the frame; the rocket forces pull its ends apart. They are the new *causes* in play.

A different example, needing only kinematic variables to explain it, gives a detailed analysis of Lorentz contraction in acceleration. Let us ask:

i Is there an acceleration pattern for a whole thread that, with respect to its original frame, results only in its Lorentz contraction?

ii Does this pattern have the result that the rod has the same length with respect to every momentarily co-moving inertial frame [mcif]?

iii Does the make up of the rod play any role in the outcome if accelerated in this way? I.e. would a soft rubber rod be contracted differently from a steel or wooden one?

These questions are about only kinematics (geometry) of the acceleration.

Uniform acceleration (hyperbolic motion) of a point settles the first two questions affirmatively. The points at unit spacelike interval from the origin O of a Lorentz coordinate system in 2-dimensional spacetime form a hyperbola (we need consider only one lobe). So do the points at 2 units spacelike interval from O. These hyperbolae are asymptotic to the light cone in that quadrant of spacetime. Imagine these hyperbolae as endpoints of an accelerating unit-length thread. Any spacelike line through O that intersects the first hyperbola will intersect the second and each segment so defined will be both a unit spacelike length, and a unit *spatial* length with respect to each mcif. Let every other point in the rod have a corresponding hyperbolic acceleration, constant in its interval from O. The equations of motion of the end points are:

$$t^2 - x^2 = 1^2 \qquad\qquad t^2 - x^2 = 2^2$$

The equation of motion of each thread-point at R ($1<R<2$) will be

$$t^2 - x^2 = R^2$$

In each mcif the thread has unit length; the x mcif coordinates of the force fields that define the structure of the thread are the *same* in each frame. The thread at any moment is Lorentz contracted relative any earlier frame as a function of its velocity in that frame. At each spacetime point on the worldline of a thread-point, the acceleration 4-vector is the same in magnitude and orthogonal to the velocity 4-vector at the point. The directions and magnitudes of the acceleration 4 vectors attached to different thread-points vary continuously with R.

The example may be generalised by appropriately increasing the magnitude of the constant acceleration vectors i.e. the curvatures of the various worldlines for each thread-point. [10]

The example is idealised. It assumes a continuous thread. Characterising the different point-accelerations captures the accelerated Lorentz contraction of an extended rod. Real threads and rods are complex. To characterise force fields that could cause the pattern would involve enormous difficulties, varying from rod to rod. In real rods, quantum structures forbid continuous matter. Further, the forces must differ in ways we have only vague pictures of − different materials present different dynamical problems, with different internal micro variations of mass even in highly homogeneous cases. Here, at last, is a serious issue of dynamics that depends on how the rod is made up. However, such dynamical complications are not directly relevant to an accelerated Lorentz contraction. Appropriate constant accelerations for each point fully explain that. Such a description draws only on the nature of the spatio-temporal environment in which the acceleration occurs.

Thus the Lorentzian pedagogy, as Bell presents it, nowhere unequivocally draws on dynamics. Nor can it restore confidence in perfectly sound and useful concepts already acquired.

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ENDNOTES

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[1] Numbers in brackets refer to pages in Bell's paper. I am indebted in this paper to Angas Hurst, Michel Janssen, Peter Lavskis, Steve Leishman, Stephen Lyle, John Mercier, Colin Mitchell, Chris Mortensen Peter Quigley and Peter Szekeres.

[2] Wherever appropriate, I italicise 'Fitzgerald' in the hope of avoiding unconscious readings of 'Lorentz'. The phrase 'Lorentz contract' occurs just once in the paper (75). '…in the rocket problem of the introduction , the material of the rockets, and of the thread, will Lorentz contract. A sufficiently strong thread … would impose Fitzgerald contraction [sic] on the combined system'. Grammar suggests a reading in which the phrases refer to the same contraction; or, implausibly, that the one contraction imposes the other. The rocket problem is discussed in §5 below.

[3] The analogy between moving and cooling rods contracting is made by Lorentz himself in his (1916) p. 196):

> "We may, I think, even go so far as to say that that, on this assumption [i.e., the contraction hypothesis], Michelson's experiment proves the changes of dimension in question, and that the conclusion is no less legitimate than the inferences concerning the dilatation by heat or the changes of the refractive index that have been drawn in many other cases from the observed positions of interference bands."

See sec. 3.5.5, note 111 of Janssen (1995).

[4] Unlike Feynman, for example, Bell manifests neither sympathy nor antipathy toward philosophy nor an understanding of it. In a footnote that *appears* directed at the 'old problem' discussed in sec 6 of the present paper, he complains that failure to follow Lorentz's pedagogy may 'set off premature philosophizing about space and time'. Bell's discussion of it makes 'premature' apposite. We are left to guess what makes it philosophical.

[5] I am indebted to Michel Janssen for pointing to a possible connection between Bell's non-committal on this aspect of his Lorentzian pedagogy and his proposal that a return to FitzGerald, Lorentz, and Larmor might be the price we have to pay for having instantaneous measurement collapses in QM. See Janssen (1995) Section 2.3.5, note 63) and Balashov and Janssen (2003, p. 336). Bell made this proposal in a well-known interview published in Davies and Brown (1984 p. 49).

[6] Bell nowhere says what mystification lies in relativity's Lorentz contraction or at how his approach avoids it.

[7] There are two provisos. First, that we should assume all relevant laws Lorentz covariant; the other is discussed in §5 below.

[8] Lyle (2010) gives a careful, perceptive analysis the problem of a rod accelerated as rigid, including not only the kinematics of accelerating points, but also the problem of what forces could accelerate a rod in this way. Its approach to the problem through rigidity differentiates it from Bell's interest, but a comparison makes clear how much more careful and insightful Lyle's treatment is. See especially §§1.1, 1.2, 1.7

[9] Janssen (2009 §3.5) argues that the principle/constructive distinction is something quite separate from the dynamics/kinematics distinction.

[10] For a complete discussion see Rindler 1969; alo also Misner et. al 1973 §§6.1, 6.2; Schutz 1985 pp. 56, 150 where it is the subject of student exercises.