

On the Epistemic Control of Theories, and Our Lack of It in Quantum Gravity

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– Wallace Stevens –
“Thirteen Ways of Looking at a Blackbird”, VIII

I know noble accents
And lucid, inescapable rhythms;
But I know, too,
That the blackbird is involved
In what I know.

[W]e are met as cultivators of mathematics and physics. In our daily work we are led up to questions the same in kind with those of metaphysics; and we approach them, not trusting to the native penetrating power of our own minds, but trained by a long-continued adjustment of our modes of thought to the facts of external nature.

– James Clerk Maxwell (1870)
“Address to the Mathematical and Physical Sections of the British Association”

The subtlety of Nature far exceeds the subtlety of sense and intellect: so that these fine meditations, and speculations, and reasonings of men are a sort of insanity, only there is no one at hand to remark it.

– Francis Bacon
Novum Organum, Book I, Aphorism X

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BHT $\Rightarrow$ QG?

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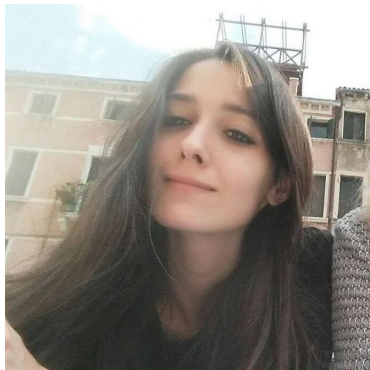
An Empirical Rendition for QG? Its Regime of Applicability?

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BHT $\Rightarrow$ QG?

- going to be as **contrary, crotchedy and cranky** as I possibly can—which is a lot—on QG
- partly because most physicists themselves won't do it. . .
- philosophers defer too much to the physicists. . .
- but it **NEEDS DOING** to redress the imbalances in physicists' public pronouncements and private practices

– Eugenia. . .



contemplative
which one wants in a physicist

I am happy to report is one of the rare physicists who does question and constructively criticize concerning foundational issues

– Karen. . .



saucy
one of the finest traits possible for a philosopher

I suspect will be skeptical and critical, in her inimitable way. . .
although perhaps not enough for my taste

– but mostly I shall be contrary, crotchedy and cranky because Richard. . .



triumphant
but justifiably so?

will, I suspect, be so supportive, constructive and sunny as is humanly possible

(remind me to tell you, over a glass of wine, the story of the first time Richard and I met)

- a good object lesson: one can like someone tremendously, with respect and affection. . .
- and think they are an excellent philosopher or physicist. . .
- have fabulously constructive and edifying discussions with them. . .
- and yet still think they are as wrong as eating spaghetti with a spoon
- *because **talking with**—and, more important, listening to—such people is the **best way to learn***

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- physicists in some areas of physics. . .
- and philosophers in essentially every area of philosophy. . .
- promulgate theories for which we have
no principled, cogent understanding of their representational and evidential relations with the real world

much philosophical blood, toil, tears and sweat—and ink—has been spilled, suffered, shed and secreted—and wasted—

- in attempt to understand *what is empirical content* of physical theories (Plato 360 BCE (ca.); . . . ; Poincaré 1902; Reichenbach 1916–1917; Russell 1927; Carnap 1936; Quine 1948; Carnap 1956; Suppes 1962; Hempel 1973; van Fraassen 1980; Stein 1994; Friedman 2001; French 2014; Curiel 2025)
- little attention paid to epistemic conditions required *to have confidence that we can in fact fruitfully play with theory so as to further enterprise of science*. . .
- which is to say, to have *confidence* that, at a minimum, *what we think* of as the empirical content is in fact *rightly conceived of* as such. . .
- and, moreover, that we understand how to *extend our theoretical knowledge* of that empirical content into *physically significant application to the world*—
- which, indeed, itself *gives strongest evidence* that we've got *empirical content right* and have theory *otherwise under control*

– contrary to popular belief

to understand the *empirical content* of a theory (on popular construals)

is not eo ipso

to understand possible evidential relations between world and theory

broadly and crudely speaking, three categories of conditions for epistemic control:

1. empirical/experimental ('E' in following)
2. evidential/epistemological ('V' in following)
3. theoretical/methodological ('T' in following)

- speciation, classification, is always a dicey game—one should have good reason for it
- in this case, I hope to make it easier to present and easier for audience to digest a complex and unwieldy idea
- I'm not entirely happy with the classification. . .
- neither with its carving nor with the need for the carving
- there are many possibly misleading connotations
- and many of the conditions do not fit easily under any one category. . .
- but I think the risk is worth the gain in the ability to hold the key ideas more easily in one's mind at once

epistemic control consists in *having an understanding*, to some degree, of some (non-trivial) subset of the following:

1. empirical rendition [E]
2. evidential warrant for [V]
3. why theory needed [E,V,T]
4. regime of applicability (*a fortiori* breakdown scales) [E]
5. asymptotics of quantities and dynamics [T]
6. justified approximations and idealizations [T]
7. detectable coupling of quantities, evolutions [E,T]
8. schematization of the observer [E,T]
9. legitimate forms of argumentation [T]
10. physical significance/physicality of formalism [E]
11. what it may take to give interpretation [T]
12. for evidential warrant [V]
13. relations to other theories [E,V,T]
14. relations among different formulations [T]
15. categorial/foundational concepts/issues [T]

very roughly speaking, satisfaction of *each necessary* to satisfy *every one below*

in a little more detail:

1. *empirical rendition*: some understanding of *how the theory can make contact with empirical data* that we have in hand, or that we can foresee how to acquire in a way compatible with the experimental component of the current epistemic state
2. *what will and will not count as evidence* in favor and against, and why
3. *why* is the theory *needed*? inexplicable experiments, indirect empirical evidence, to save an important physical principle, purely theoretical reasons, purely pragmatic reasons, purely aesthetic reasons, metaphysical commitments, . . .
4. *regime of applicability* and so, *a fortiori*, its *breakdown scales*
5. to understand the *asymptotics of physically important quantities and dynamics*
6. to understand *what approximations and idealizations are justified*, and why

7. to understand which of the system's *quantities may couple in detectable ways* with possibly appropriate—and, in the best of cases, technically feasible—experimental devices and arrangements, and which *states of the system will possess appropriate values* of those quantities and *which courses of dynamical evolution* in, from or to those states will support the needed interactions
8. to understand the *conditions* under which we do and do not need *explicit schematization of the observer*, and to understand how to do it in concrete detail
9. to understand *what forms of argumentation* (e.g., heuristic, perturbative, etc.) *are legitimate* in different investigative contexts in the ambit of the theory, and why
10. to understand as well what is the *physical significance* of the different and various kinds of the structures, entities, components, . . . , of the *theory's formalism*
and so to understand the *kinds of physicality those parts all respectively can have*, and the circumstances in which they respectively can have them
11. and so how we *may be able to give a satisfactory and complete interpretation* of the theory, even if we in fact cannot do so at the moment

12. some understanding of when and why the theory has accrued enough evidential warrant for *it itself to have the capacity in turn for its claims to serve as evidence* for further scientific assertions
13. to understand the theory's *relations to other valuable theories* (theories precedent to the theory itself, and theories laterally and antecedently related in an epistemic, conceptual or practical sense)—not just by approximation and limiting relations and such, but also *relations among concepts*
14. when there is *more than one formulation* of the theory and they differ to a degree that their interrelations are not perspicuous (as in SCG and BHT!), to *understand how they relate*, formally, conceptually and interpretively, in such a way as to treat the same family of physical systems
15. some understanding of *how to investigate the standing of categorial and other foundational concepts*, principles and problems in the context of the theory (Curiel 2009), e.g., determinism

empirical/experimental

1. empirical rendition
2. why theory needed
3. regime of applicability (*a fortiori* breakdown scales)
4. detectable coupling of quantities, evolutions
5. schematization of the observer
6. physical significance/physicality of formalism
7. relations to other theories

evidential/epistemological

1. evidential warrant for
2. why theory needed
3. for evidential warrant
4. relations to other theories

theoretical/methodological

1. why theory needed
2. asymptotics of quantities and dynamics
3. justified approximations and idealizations
4. detectable coupling of quantities, evolutions
5. schematization of the observer
6. legitimate forms of argumentation
7. what it may take to give interpretation
8. relations to other theories
9. relations among different formulations
10. categorial/foundational concepts/issues

- roughly speaking, *satisfaction of each* condition in the list is *necessary* to satisfy *every one below* it
- the situation is more complex than that, however, when one tries to examine it with more finely-grained acuity. . .
- in practice, to acquire the ability to recognize the state of affairs required to satisfy each condition. . .
- or, what is more important from a foundational point of view, to acquire *the epistemic capacities* required *to satisfy each* condition. . .
- is a dialectical process involving the *advancement of several conditions at once*, each buttressing the others in inextricably mutual and complementary ways

- epistemic control *en bloc* comes in *gradations*. . .
- as does the *satisfaction of every condition* in the list
- it may happen, moreover, and likely always does happen, that we will have achieved *progress for different “parts”* of a theory with respect to *different conditions* to *different degrees*

- list *not* intended to be *exhaustive*, merely *exemplary*
- although I have *hopes* to have captured most of the *most important provisions*
- I strongly suspect there is, in principle, *no complete, final, canonical* such iteration and explication of its provisions, a κτήμα ἐς αἶν, *semper eadem*
- but rather, as the nature of our *theorizing evolves*, and novel forms of theory arise. . .
- *novel conditions* for epistemic control will correlatively *arise*. . .
- and perhaps some *existing* ones will fall into *desuetude*
- if, for example, contemporary craze for gauge/gravity dualities (such as AdS/CFT) were ever to bear real fruit, what it would mean to have epistemic control over such a theory would certainly involve novel conditions, to control the duality itself

- one can always meaningfully talk about the epistemic control of individual researchers. . .
- but one can do so for an entire community only after the theory has achieved some degree of maturity. . .
- which includes significant consensus on whether, how and to what degree many, although not necessarily all, of the theory's parts and their applications stand *vis-à-vis* the conditions for epistemic control
- this has not yet happened for any subcommunity of QG (particular program), much less for the entire community (all programs in aggregate)

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empirical rendition

some understanding of how the theory can make contact with empirical data

- may be *much less* than *complete interpretation* of formalism
- *much less* than thorough understanding of *physical significance* of entities and structures of formalism
- and *much less* than direct and decisive *empirical support*
- requires, at a minimum, to have some understanding of *what direct connection to empirical data would be* for the theory
- can, for example, and often will, consist of much less than something like Carnapian correspondence rules or Reichenbachian coordinating principles or Tarskian/Beth semantics, or possible-world semantics or contemporary Shiboloth of “representational capacities” or . . .
- for we want to allow physicist to *meaningfully investigate a theory*, both theoretically and experimentally, when much about it, including *much of its epistemic content, is not yet known*

- to have an *empirical rendition* is the one condition that is *necessary* for epistemic control
- rest are individually important. . .
- but any one may not yet have been achieved by researchers in the field. . .
- while they still have some modicum of epistemic control
- nonetheless, one *cannot have an empirical rendition without also* satisfying at least to some minimal degree *some of the other* conditions. . .
- not always the same subset in every case. . .
- neither in the case of an entire theory nor in the case of different parts of the same theory

beautiful, profound, extraordinary, groovy, sexy, mind-blowing,
... , example:

Hertz's (1892) search for ways to produce and to
measure electromagnetic waves based on a manifestly
partial empirical rendition of Maxwell theory

example – gravitational waves:

- Einstein introduced idea in 1916
- struggles over next 40 years to understand whether the purported phenomena was physically real, or just coordinate artifact
- $\Rightarrow$ *much confusion in community*
- $\Rightarrow$ *GR empirical rendition lacked understanding of this phenomena*
- sign of this: no one had **any idea how to build a detector** that would be sensitive to—and *only* to, in the relevant sense—gravitational waves until the mid-1950s
- $\Rightarrow$ didn't understand:
 1. evidential warrant
 2. regime of applicability, breakdown scales
 3. asymptotics
 4. justified approximations, idealizations
 5. detectable coupling of quantities. dynamics
 6. schematizing the observer
 7. forms of argumentation
 8. physical significance
 9. categorial concepts, issues

⇒ all that also lacking from epistemic control over GR

- Pirani (1957) gave first, albeit partial, physically significant contribution to GR empirical rendition with regard to gravitational waves
- sign: almost immediately after, consensus on how test particles would respond to passing gravitational wave, based in part on Pirani (1956) (itself indebted to Synge 1934)
- very soon thereafter, Weber, *inter alia*, developed important account of concrete ideas for practical, possible gravitational wave detectors in the laboratory. . .
- including details necessary for complete understanding of schematizing the observer:
 1. how to design instruments and configure them in experiments
 2. understanding of what the detector is (should be) *insensitive* to (in this case, cosmic rays)
 3. and so how to distinguish signal from (in this case thermal) noise
 4. . . .

⇒ account of how to recognize what counts as evidence of detection

example – black holes (Curiel 2019b):

- the use of asymptotically flat black hole with a standard event horizon as idealization of an “isolated” black hole. . .
- is under epistemic control for all current observational purposes (SgrA* as Kerr for EHT, coalescing binary black holes as Kerr pair for LIGO/VIRGO etc.)
- and many, if not most, theoretical applications in classical GR

- it is, however, *not* under epistemic control in more *recherché* contexts. . .
- such as the Hawking effect, black hole evaporation and discussions of the Information-Loss Paradox (Curiel 2026)
- indeed, one can argue that it is exactly the illegitimate use of that idealization, the attempt to employ it beyond its conceptual regime of propriety, our lack of epistemic control of it in those investigative contexts. . .
- that leads to all the confused brouhaha about information loss
- intimately related: little to no understanding of:
 1. what can count as evidence in favor
 2. regime of applicability and breakdown scales
 3. asymptotics of quantities and dynamics
 4. schematizing the observer
 5. legitimate forms of argumentation
 6. physical significance
 7. how all the *many* different frameworks relate to each other
 8. . . .

To paraphrase Jorge Luis Borges ("La Postulación de la Realidad", 1931):

[Física] no escribe los primeros contactos de la realidad [en matemáticas], sino su elaboración final en concepto.

⟨[Physics] does not write reality's initial contacts [in mathematics], but rather its final elaboration in concepts.⟩

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A physical principle cannot be said to be true until it has been shown to be false and its envelope of applicability delineated.

– Sheldon Glashow (1999)
“On Being Almost Lorentz Invariant”

- it is appreciated that one must analyze and control for errors and selection (and other) biases in empirical data. . .
- in ever more sophisticated ways as experimental precision and resolution increase
- perhaps not so widely recognized that theories and theoretical models, both in themselves and when used to structure and interpret data, *require the analogous*. . .
- delimiting the *regime of applicability* of those theoretical tools

- it is characteristic of appropriately unified kind of physical system, treated by a single theory, that there exist a set of scales at each of which all theoretical quantities simultaneously lose definition
- every theory, in so far as it treats an appropriately unified kind of physical system, not only has a regime of applicability, but it has a *single, unified* one, bounded on all sides by scales characterized by the values of different combinations of its quantities
- for Navier-Stokes fluids, *e.g.*, the definitions of pressure, fluid flow, viscosity, . . . , break down at spatial and temporal scales a few orders of magnitude greater than the mean free-path of the constituent molecules
- all quantities also lose definition when the fluid enters a strong enough state of turbulence, which can be characterized by (*inter alia*) a ratio of the fluid's kinetic energy to a measure of its viscous damping—a scale independent of that characterized by the mean free-path

This seems, indeed, to be one of the markers of a physical theory:

- the existence of a set of characteristic scales for its physical quantities
- at each of which all the theory's physical quantities simultaneously lose definition—
- “places” where all the kinematically and dynamically relevant structures of the theory break down all at once
- in the sense that the theory becomes inadequate for an appropriate treatment of any system beyond the determined boundaries

- although we perhaps naively tend to think of scales determined by spatial, temporal and energetic quantities when considering how and where theories break down in their capacity to provide sound representations of phenomena, any quantity in any theory can provide such a measure
- velocity provides a breakdown scale for Newtonian mechanics
- acceleration and scalar curvature provide different breakdown scales for various theories of gravity, such as GR
- no breakdown scale, moreover, can be a single number holding for all systems the theory treats
- Navier-Stokes theory, for instance, becomes inadequate for different fluids at different energies and spatial and temporal scales

- often it is not a bound on a single quantity, such as a value of energy, a value of spatial length, *etc.*: classical Maxwell theory, *e.g.*, breaks down when the ratio of the field's amplitude to its frequency approaches $\hbar$
- nor is it ever the case that there is a single characteristic scale for each theory
- Navier-Stokes theory breaks down:
 1. when various measures of flow complexity indicate the fluid is approaching turbulence
 2. when the fluid is too viscous
 3. over time scales comparable to equilibration time after a sharp disturbance
 4. when temperatures become large enough that heat loss due to emission of blackbody radiation becomes non-negligible
 5. when ambient electromagnetic field becomes strong enough to ionize the fluid's constituent molecules
 6. and on and on

- all of which shows, moreover, that sometimes a breakdown scale is determined by physical quantities not even representable in the theory (such as the electromagnetic field for Navier-Stokes)
- sometimes, moreover, approximations used to construct models of particular behavior, such as surface waves in fluid dynamics, have characteristic breakdown scales different from those of the material in which the phenomena manifest (Lamb 1932, ch. IX)
- in such cases, the theory can provide appropriate and adequate models of the systems in the relevant states, only not in the way the approximations definitive of the behavior at issue require

A breakdown scale, then, is something like the following:

a measure of or function of or relation among quantities, such that, when the joint state of the system and its environment imply that the values of some of the system's quantities do not satisfy the measure, function or relation, then the theory can no longer provide good models of the system

- breakdown scales can *never* be determined by analysis of *the formalism and theoretical machinery of the theory alone*, without input from knowledge acquired by experimentation in particular and empirical investigation in general
- they are rather fixed by knowledge that one can gather only from investigations grounded in that part of the epistemic content of the theory not captured by the formalism by itself, largely in experimental and observational practice
- as such, they change with the increasing scope and depth of our experimental reach

what does it mean to say that the theory cannot provide good models of systems outside its breakdown scales?

- one of the most important markers of this is that the system's quantities lose unambiguous definition with respect to the theory's resources for modeling them
- for a Navier-Stokes fluid, for example, different sorts of thermometers that allow spatial discrimination on scales only a couple of orders of magnitude greater than the mean free path of the fluid's molecules will record markedly different "temperatures" depending on characteristics of the joint system that one can ignore at larger scales—the fine details of the fluid's convective flow in relation to the geometry of the thermometric system, for instance, and even the transparency of each thermometer to the fluid's particles¹
- as the fluid approaches turbulence, to take another example, the values of all its quantities begin to vary rapidly in time and eventually cannot be measured by any conventional means—the quantities are no longer well defined

1. See, e.g., Benedict (1969) for detailed exposition of the complex interplay among theory, model and experiment one must take account of in attempting to define a physical quantity such as temperature based on the behavior of real measuring devices.

without knowledge of a theory's regime of applicability, and in particular when a given system of interest lies in its scope, we have *no grounds whatsoever* for trusting what the theory purports to say about the system

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- One can view physical theory, to some degree, as the rational reconstruction of experiment and data, as some formally minded philosophers seem to intend.
- One can also view theory, to some degree, as the codified articulation of a metaphysics and ontology, as other formally minded philosophers seem to intend.
- But both only to some degree, and neither one high enough to keep one warm on the long, dark, empty winter nights of the realized barrenness of one's reconstruction or articulation—
- Now that you have it in hand, what will you do with it? What problems will it solve, or even illuminate?

Ones of a purely formal character, no doubt.

- The contents of the concepts we deploy in our reasoning in physics and in the consequences we draw from it—
- the concepts whose inter-relations constitute the claims we make in all of it—
- are not exhausted by the mathematics, nor by “interpretations” of the mathematics, much less by statements of what the mathematics represents.
- The concepts are informed by *all* aspects of scientific practice, including the messiness of experimentation and the meshugas of observation, much of which cannot be captured by the mathematics. . .
- and much of that, when the mathematics is involved, cannot be clearly disentangled from the mathematics.

THE METHODOLOGY

Treat matters as epistemological so far as possible, moving into metaphysics only so far as necessary, and then always grounding it in and constraining it by the knowledge and understanding one has acquired, in conformity to the epistemological principles one works with.

- the miracle of science is that theory and experiment are consonant with each other—
- the necessity of science is that they are inextricably so. . .
- not, however, as equals

— — —

Theory plays Boswell to the subtle and tragic clown
of experiment's Johnson.

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what is QG?

it's just this thing, ya know?

different conceptions:

1. to construct a quantum theory of GR
2. to incorporate gravity into the Standard Model of partical physics
3. to unify the Standard Model of partical physics and GR
4. to construct a framework *ab initio* independent of GR and the Standard Model that does something or other important

a large, sprawling, ever-growing, endlessly variegated menagerie:

1. canonically quantized GR
2. spin-2 massless field
3. path integral
4. loop quantum gravity
5. string theory
6. gravity from thermodynamics (SEVERAL!)
7. causal set theory
8. causal dynamical triangulation
9. asymptotic safety
10. group field theory
11. causal fermion systems
12. Euclidean QG
13. dilatonic QG
14. gauge-gravity dualities (MANY!)
15. holographic programs (INNUMERABLE!)
16. Hořava-Lifshitz gravity
17. non-commutative geometry
18. shape dynamics
19. Regge calculus
20. twistor theory
21. supergravity
22. ...

why do we need QG?

(epistemic control condition #3)

- what is it one wants from a theory of QG that would incorporate the best or deepest or ... of both QT and GR?
- a theory of QG should combine GR and QT in a way that holds on to (as much as possible of) what is most characteristic of each as an account of the way that the relevant part of the physical world works. . .
- the deepest lessons each has taught us about the nature of the world
- it would also be wonderful if the theory of QG resolved what I see as the deepest conceptual problems, respectively, of each theory

what one may want to keep in a deeper theory, and why, for GR (Penrose 1969, pp. 1148ff.; Curiel 2017):

1. the geometric nature of “gravity”—its inextricability from “space-time”, that it is not a separate force or interaction, as electromagnetism is
2. ultimately this means that, no matter exactly what the field equations may be (Einstein’s or otherwise), above some spatiotemporal scale and below some energy scale spacetime and gravity are jointly well modeled using the machinery of Lorentzian geometry
3. causal structure—not only the constraints on dynamics and possible symmetries of physical systems that the structure of a Lorentz metric imposes. . .
4. but also, orthogonally, the fact that the causal structure of a spacetime alone already gives one essentially $9/10$ of the metric²

2. To know the metric up to a conformal factor fixes everything but the volume element.

I think the deepest conceptual problem of GR, given the way that we tend to try to think about the world:

GR gives no principled, clear grounds to distinguish between “matter” and “geometry/gravity” (Curiel 2017)

- the “obvious” way to distinguish them—matter is Ricci curvature, gravity is Weyl curvature—doesn’t really work. . .
- “Weyl curvature can transform into matter” (e.g., the Hawking effect)
- but also “matter transforms into Weyl curvature” (e.g., gravitational collapse to a singularity)
- perhaps this suggests that, at some deeper level, “matter” and “curvature/gravity” are just different manifestation of an underlying unified entity?

what one may want to keep in a deeper theory, and why, for QT (Curiel 2021, 2022):

1. what is encoded purely in the structure of the dynamics—
2. what you can tell me about the nature and dynamics of a system if I give you its algebra of observables and its possible states
3. this includes:
 - 3.1 entanglement (*not* necessarily superposition, which is a basis-dependent notion—a “privileged basis” makes no sense to me—although it may be that there can be no entanglement in the relevant sense without basis-dependent superposition)
 - 3.2 conservation of probability for the evolution if anything like the Born Rule is fundamental (not necessarily unitarity, but it would be nice to have)

I think the deepest problem, again given the way we tend to like to try to think about the world:

there is no clear distinction between, on the one hand, interaction between separate systems and, on the other, dynamical evolution of a single system (Curiel 2022)

- in classical physics, a dynamical evolution is represented by a vector field on the space of states
- an interaction with another system consists of an externally imposed force (a “generalized force” in Lagrangian mechanics), which is represented by a *different kind* of vector field on the space of states
- dynamical evolution and interaction are mathematically, physically and conceptually distinct
- correlatively, one can always, without ambiguity, separate the degrees of freedom of a given system from those of any other systems it may be interacting with
- and there is always a distinguished “free-evolution dynamical vector field” (“isolated system”), identifiable from the internal structure of the dynamics alone
- in QT, dynamical evolutions are generated by exponentiating a self-adjoint operator (the “Hamiltonian”)—

- but interactions are *exactly the same thing*, just adding on the exponentiation of another Hamiltonian
- they are mathematically, physically and conceptually *not* distinct, but, again, seem to be different aspects of some underlying unified conceptual structure that we have not adequately articulated and grasped
- correlatively, it is *not always possible to cleanly separate the degrees of freedom* of a given system from those of others it is interacting (“entanglement”)
- and there is *NO* distinguished “free-evolution dynamical vector field” (no sense of “isolation”) identifiable from the internal structure of the dynamics alone
- this, I think, is the heart of the Measurement Problem

- best of all would be for a theory of QG to solve both problems. . .
- and that in a way that shows them to be related to each other—
- for it seems to me an evocative and compelling idea that the lack of a clear distinction between interaction and evolution in QT is intimately connected with the lack of a clear distinction between matter and geometry in GR

- What, however, is the *necessity*, if any, for the development of a theory of QG?
- Why not be satisfied with a semi-classical treatment of gravity of some form, classical geometry coupled to some function of quantum matter (e.g., SCG and the SCEFE)?

NO EMPIRICALLY GROUNDED
REASON

arguments all wholly theoretical, pragmatic, æsthetic, metaphysical or otherwise aspirational:

- *Gedankenexperimente* (mostly crappy)
- “the world is quantum; gravity must be too!”
- “GR breaks down at singularities!”
- “string theory is pretty!”
- “the mettle of physics demands a unified theory of everything!”
- “divergences in quantum field theory $\Rightarrow$ missing degrees of freedom from quantum gravitational field!”
- “BHT: entropy = area $\Rightarrow$ gravitational micro-states!”
- “I can’t understand the world until I have a primitive, fundamental, . . . , ontology, and that is given by a theory!”
- “I need something sexy for my grant proposal!”

some are more compelling than others

standard example:

1. gravity (spacetime, geometry) is a physical theory
2. all (other) known physical theories are subject to QT
3. *ergo*, so should gravity be (GR)

why I find this unsatisfying:

- GR already tells us that the “universality” of the gravitational features/properties of matter fields does not apply to gravity itself. . .
- that universality is expressed in the fact that all matter fields contribute in the same way to T_{ab} (on the RHS of the EFE)
- but gravity does not at all (Curiel 2019a)
- thus, GR itself tells us that gravity is special. . .
- different from all other fields to which QT straightforwardly applies—
- this is a tension, possible incompatibility between GR and QT

a small selection of references:

1. inaugural papers by Bronstein, Infeld, Rosen, and Fierz and Pauli from the 1920s–1930s
2. Anderson et al. (1957[2011])
3. Rosenfeld (1966)
4. Eppley and Hannah (1977)
5. Unruh (1986)
6. Giulini and Kiefer (1995)
7. Isham (1994)
8. Rovelli (1998, 2001)
9. Huggett and Callender (2001)
10. Wüthrich (2005)
11. Mattingly (2005, 2006)
12. Carlip (2008)
13. Rydving et al. (2021)

Mise en scène

Epistemic Control – A *Précis*

Empirical Rendition

Breakdown Scales and the Regime of Applicability

Epistemology, Not Metaphysics

What Is Quantum Gravity, and Why Do We Need It?

An Empirical Rendition for QG? Its Regime of Applicability?

The Revelations and the Revelators

BHT $\Rightarrow$ QG?

If a lunatic scribbles a jumble of mathematical symbols it does not follow that the writing means anything merely because to the inexperienced eye it is indistinguishable from higher mathematics.

– Eric Temple Bell (1937)
Men of Mathematics

we've already examined one aspect of our lack of epistemic control over QG: why we need it

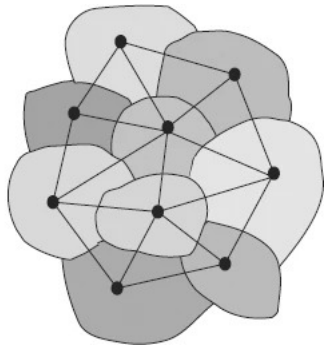
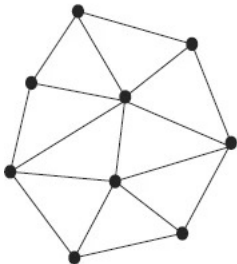
now let's focus on whether we can, or what it would take to:

1. attribute an empirical rendition
2. sketch regime of applicability and breakdown scales

study of how QG in general, and programs in particular, may or may not satisfy other conditions would be excellent project for some eager youngsters!

loop quantum gravity (LQG):

1. the structure of space and time is composed of infinitesimally small but finite “loops” linked in a complexly woven network (“spin network”)
2. each node in the network “represents a chunk of space”:



(shamelessly cribbed from Rovelli 2008)

Rovelli (2008):

The central physical result obtained from loop quantum gravity is the evidence for a physical quantum discreteness of space at the Planck scale. This is manifested in the fact that certain operators corresponding to the measurement of geometrical quantities, in particular area and volume, have discrete spectra.

- area operator: counts lines in a spin network, corresponding to faces in the associated spin foam $\Rightarrow$ geometric AREA!
- volume operator: counts vertices in a spin network, corresponding to lines in the associated spin foam $\Rightarrow$ geometric VOLUME!

- area and volume operators seem, *prima facie*, to give us at least the start of an empirical rendition
- BUT: these are in fact **NOTHING LIKE** ordinary spatial area and volume in **ANY** known sense
- Rovelli talks blithely of their “corresponding to the *measurement* of geometrical quantities” . . .
- but no measurement procedure is ever proffered, whether related to “ordinary” spatial measurements or not
- only methods for computing the operator spectrum for a given state

I strongly feel we still do not yet have a satisfactory empirical rendition for LQG

regime of applicability and breakdown scales – the Planck scale

- one can combine the fundamental constants of nature (G , c , $\hbar$ and k_B) so as to derive quantities with every physical dimension (energy, mass, spatial length, temporal interval, temperature, ...), the Planck units:

1. $l_P = \left(\frac{\hbar G}{c^3}\right)^{1/2} = 1.6 \times 10^{-37} \text{ cm}$

2. $t_P = \left(\frac{\hbar G}{c^5}\right)^{1/2} = 5.4 \times 10^{-44} \text{ s}$

3.

4. $E_P = \left(\frac{\hbar}{G c}\right)^{1/2} = 1.2 \times 10^{28} \text{ eV}$ (max LHC is $13.6 \times 10^{12} \text{ eV}$)

$$m_P = \left(\frac{\hbar c}{G}\right)^{1/2} = 2.2 \times 10^{-5} \text{ g}$$

- Planck scale: a paradise currently unavailable but will solve all problems (singularities, dark energy/matter, fine tuning, ...) when we achieve it

what is the Planck scale physically?

- consider the Planck length...
- is it the scale at which QG effects predominate?
- the scale at which classical spatiotemporal/geometrical structure “breaks down”?
- something else?
- evidence from LHC and from perturbing standard couplings and looking at RG flows suggest that Standard Model is just fine all the way up to the Planck scale
- many arguments for fundamentality of Planck scale follow this pattern: *one* way of measurement leads to the conclusion
- but one should never underestimate the ingenuity of experimentalists...
- they'll always find a new way to extract information in novel ways of probing systems

- for instance, the popular argument that two limits on “localization of a particle”—viz., those determined by Schwarzschild radius and by Compton wavelength—are equal at the Planck scale, and so any attempt to measure it will collapse to a black hole. . .
- is terrible
- in QT, localization depends on *variance* of spatial location. . .
- but why should stress-energy density track that?
- in GR, the formation of a black hole has nothing to do with the spatial configuration of the collapsing particle

I strongly feel we still do not yet have a remotely satisfactory understanding of the breakdown scales and the regime of applicability of any program of QG

Mise en scène

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How can you stand living like this? It's not right to lie all the time, never letting people know what's true and what's false. Is it possible that for you it's all the same... everything?

– Federico Fellini
“8 $\frac{1}{2}$ ”, Luisa to Guido

- these theoretical physicists proclaim their Good News verily like John the Revelator—
- for they bring news as well of much that one may well foresee as apocalyptic
- the way they proffer and attempt to promulgate their proposals. . .
- does damage to science on many levels, from many different directions:
 1. public perception and trust
 2. raising and cultivating young theoretical physicists to believe that physics can be done by only playing with mathematical contraptions without the prospect, much less the fact, of contact with empirical data

Curiel (2001)

Mise en scène

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– David Hume –

An Enquiry Concerning Human Understanding, Section I, Part III

When we run over libraries, persuaded of these principles, what havoc must we make? If we take in our hand any volume; of divinity or school metaphysics [or “theoretical physics” divorced from all contact with experiment], for instance; let us ask, Does it contain any abstract reasoning concerning quantity or number? No. Does it contain any experimental reasoning concerning matter of fact and existence? No. Commit it then to the flames: For it can contain nothing but sophistry and illusion.

– Steve Martin –
“A Wild and Crazy Guy”

Ahhh, it's so hard, ya know, it's so hard to believe in anything anymore, ya know what I mean? It's like religion, you can't really take it seriously, because it seems so mythological and it seems so arbitrary, and then on the other hand, science is just pure empiricism, and by virtue of its method it excludes metaphysics. And I guess I wouldn't believe in anything if it weren't for my Lucky Astrology Mood-Watch.

*I saw the best minds of my generation destroyed by madness, starving hysterical naked,
dragging themselves through the negro streets at dawn looking for an angry fix,
angelheaded hipsters burning for the ancient heavenly connection to the starry dynamo
in the machinery of night*

– Allen Ginsberg
“Howl”

– Thomas Pynchon –
Gravity's Rainbow

What bizarre shit?

BHT

- without a doubt the most widely accepted, most deeply trusted results in theoretical physics in which GR and QFT (and thermodynamics!) work together in seemingly fruitful harmony—
- especially remarkable when one reflects on the fact that we have *absolutely no experimental or observational evidence for any of it*, nor hope of gaining empirical access any time soon to the regimes where such effects may appreciably manifest themselves
- $\implies$ investigations necessarily speculative in a way unusual even in theoretical physics
- $\implies$ technically sophisticated, conceptually deep physical questions inextricable from subtle philosophical considerations spanning ontology, epistemology, and methodology, again in a way unusual even in theoretical physics
- $\implies$ why do we trust it?

a common answer:

[T]he Hawking temperature and the Bekenstein-Hawking entropy have been derived in so many independent ways, in different settings and with different assumptions, that it seems extraordinarily unlikely that they are not real.

Carlip (2014, p. 2)

consilience!

that most puissant of all epistemic tools

one of most fascinating aspects is multiplicity and multifariousness of derivations, differing radically in:

- mathematical rigor of the chosen matter + spacetime framework
- mathematical and physical character of its structures
- physical principles assumed or required
- types of physical system treated
- approximations and idealizations required
- form of conclusion
- physical origin of that form
- regime of propriety and adequacy of conclusion
- physical perspecuity and intuitiveness of them all

spacetime (GR) choices:

1. shape and character of spacetime:

- 1.1 exact solution: Schwarzschild, Kerr, Reissner-Nordström, Kerr-Newman, dS, AdS, dS-Schwarzschild, AdS-Schwarzschild, ...

- 1.2 abstract characterization:

- 1.2.1 type of horizon: event, isolated, trapping, cosmological, general causal, ...

- 1.2.2 eternal, past horizon, stationary, quasi-static, dynamic

- 1.2.3 topology: form of domain of outer communication (if a black hole); ...

- 1.2.4 symmetries

- 1.2.5 other asymptotic structure, e.g., some form of flatness or predictability

2. local or global region

3. near-horizon or asymptotic region

matter (QFT) choices:

1. QFT formulation (S -matrix, algebraic, canonical based on a Lagrangian, holographic, low-energy quantum gravity, ...)
2. flavor of QFT (scalar, vector, bosonic, fermionic, ...)
3. choice of eigenbasis needed? if so, which? or generic conditions imposed?
4. choice of state needed? if so, which? or generic conditions imposed?
5. boundary conditions

what is wanted: **radiation**

1. in some regime (energetic, spatiotemporal, ...)
2. in some region (local, global, interior, asymptotic)
3. characterized by some set of quantities, properties or behaviors:
 - 3.1 expectation values relevant quantities
 - 3.2 probability distribution over occupied modes
 - 3.3 local or a global state of a particular sort
 - 3.4 energy flux with characteristic spectrum
 - 3.5 behavior of detectors
 - 3.6 ...

common interpretation:

1. thermalized radiation is generated by the interaction of a black hole and a quantum field, with a temperature proportional to the black hole's surface gravity
2. we are warranted in thinking of the radiation as being related to the black hole itself in the same (or, at least, a relevantly similar) way as ordinary blackbody radiation is related to the ordinary hot matter that generates it
3. thus, when quantum effects are taken into account, black holes can and should be attributed a physical temperature, and thence a physical entropy
4. thus, such black holes are truly thermodynamical systems

most popular forms:

1. S -matrix $\hat{a}$ la Hawking's (1975) original
2. past-boundary $\hat{a}$ la Unruh's (1976) original
3. algebraic
4. canonical, based on Lagrangian
5. canonical, based on Cauchy evolution
6. tunneling
7. anomaly-canceling
8. more general stress-energy tensor
9. near-horizon symmetries
10. thermal atmosphere
11. holographic
12. renormalization group
13. analytic continuation
14. Euclidean path-integral
15. Lorentzian path-integral
16. low-energy quantum gravity (EFT)
17. perturbative canonical QG
18. perturbative LQG
19. perturbative string theory
20. ...

this all leaves us with (at least) 2 problems to consider:

1. is this really consilience in any appropriate sense?
2. how do all the radically different possible choices, necessities, conclusions and interpretations square with each other (if at all)?

especially because:

⇒ all suggest *radically different* physical interpretations

black hole entropy and the Generalized Second Law (GSL):

- similar multitudinousness
- many different entropies (thermodynamics/Clausius, Boltzmann, Gibbs, information-theoretic, von Neumann, other more exotic ones)
- many different, often incompatible assumptions about character of spacetime and dynamics in proofs of GSL

now, how is this all related to QG?

why ' $\Rightarrow$ ' in title: because no one knows what the relationship should be, much less what it may be, and not at all what it is (if there is one at all)

a few popular possibilities:

1. is a guide to
2. is a bridge to
3. is a gateway to
4. leads to
5. indicates presence of
6. provides evidence for
7. requires
8. is necessary for

in any event. . .

- whatever the relationship, we want to use BHT in general, and Hawking effect and black hole entropy/GSL in particular. . .
- to place constraints on “QG micro-degrees of freedom and their statistics” that “give rise to” classical spacetime geometry, or from which classical spacetime geometry “emerges”

BUT:

1. both Hawking effect and black hole entropy/GSL depend on subtle, complex interplay of affine and conformal structures of spacetime
2. some QG degrees of freedom must “give rise to” affine structure
3. some QG degrees of freedom must “give rise to” conformal structure to get second right
4. BUT the *right* QG degrees of freedom must “give rise to”, the affine structure and the conformal structure. respectively, in order to get Hawking radiation and black hole entropy right. . .
5. do they fit together in the right way?

we have no way of knowing

- we want to use SCG as basis for arguments whose conclusions we want to have confidence in—we want, essentially, to use it as part of an evidential network to buttress the assertability of claims in BHT (*inter alia*)
- but we have no entrenched empirical knowledge about SCG
- $\Rightarrow$ *it can't confer confirmation* . . .
- because one of essential elements of confirmation is that anything that gets it can then be used as evidence for other claims
- but that is exactly what Hawking radiation, BHT and SCG and such cannot do . . .
- at least not in our current epistemic state
- $\implies$ we must be careful in trying to use SCG to draw fundamental lessons!

what is going wrong? my diagnosis:

we have little epistemic control over SCG and
BHT...

and many physicists seem not to acknowledge it

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According to Unruh himself (private conversation), the article should have been titled "Why Study Quantum Gravity?"; the published title is the journal's error, doi:10.1139/p86-019.
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