Can we understand the black hole information paradox debate by studying its history?

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‘Renaissance of GR’, Dec 2015, MPIWG

Can we understand the black hole information paradox debate by studying its history?

YES!

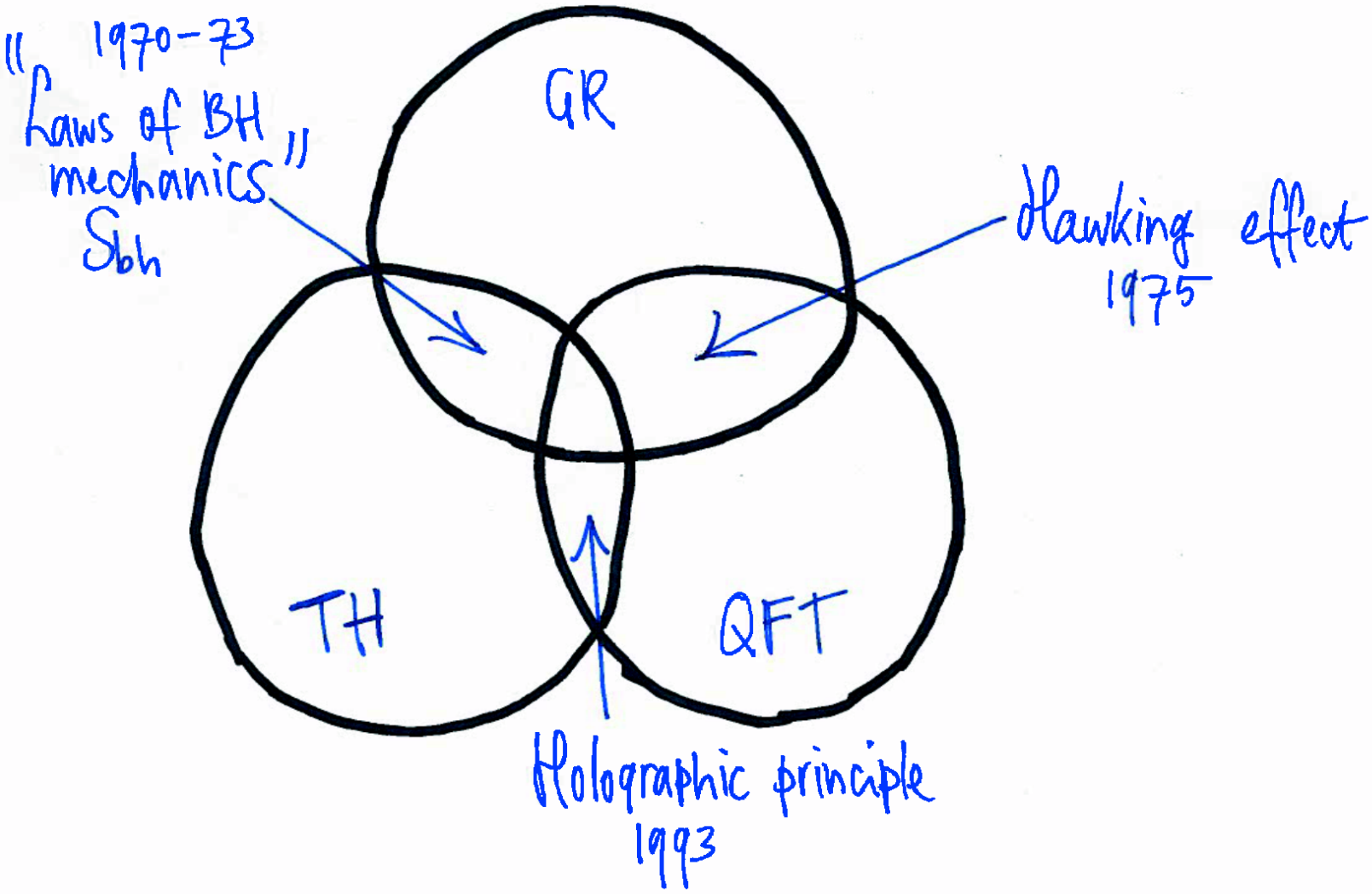
Leonard Susskind on 1993:

- “Shortly before the Santa Barbara Conference [on black holes] I had read Thomas Kuhn’s book *The Structure of Scientific Revolutions*. Generally, like most physicists, I am not very interested when philosophers opine about how science works, but Kuhn’s ideas seemed right on target; they managed to put into focus my own fuzzy thoughts about the way physics had advanced in the past and, more to the point, how I hoped it was progressing in 1993. […] I felt that the *Black Hole War* was a classic struggle for a new paradigm.”

Can we understand the black hole information paradox debate by studying its history?

YES!

BH as Borderline problem



BH as Borderline problem: ’t Hooft 1985

- “At the Planck scale it may well be impossible to disentangle black holes from elementary particles. Both carry a finite Schwarzschild radius and both show certain types of interactions. At the Planck length these objects should merge and the same set of physical laws should cover all of them.” “Although the properties of larger black holes appear to be determined by well-known laws of physics, there are some tantalizing *paradoxes* as we will explain further. Understanding these may well be crucial before one can proceed to the Planck scale.”

- “In 1985 I wrote: here is a paradox. And paradoxes are important! While searching for repairs you can make new.” [Interview 2012]

- Just like Einstein: from *constructive* to *principle* approach

Pre-history

- Laws of BH mechanics (’70-73):

$$\mathrm{d}M = \frac{1}{8}\kappa \mathrm{d}A + \Omega_H \mathrm{d}J \quad \& \quad \delta A \geq 0$$

- Bekenstein (’72-73):

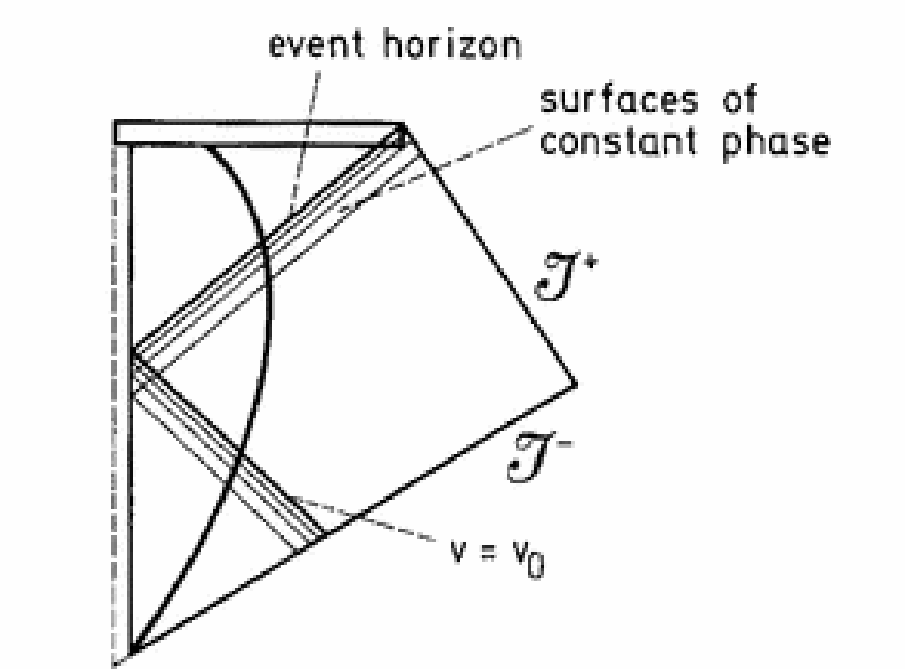
$$S = A/4$$

- Early results QFT in classical curved spacetimes (’69-73)

Hawking radiation (’74-75)

- At $\mathcal{J}^-$: $\phi = \sum(fa + \bar{f}a^+)$ & At $\mathcal{J}^+$: $\phi = \sum(pb + \bar{p}b^+)$

  Then: $a = \sum(\alpha b + \beta b^+)$



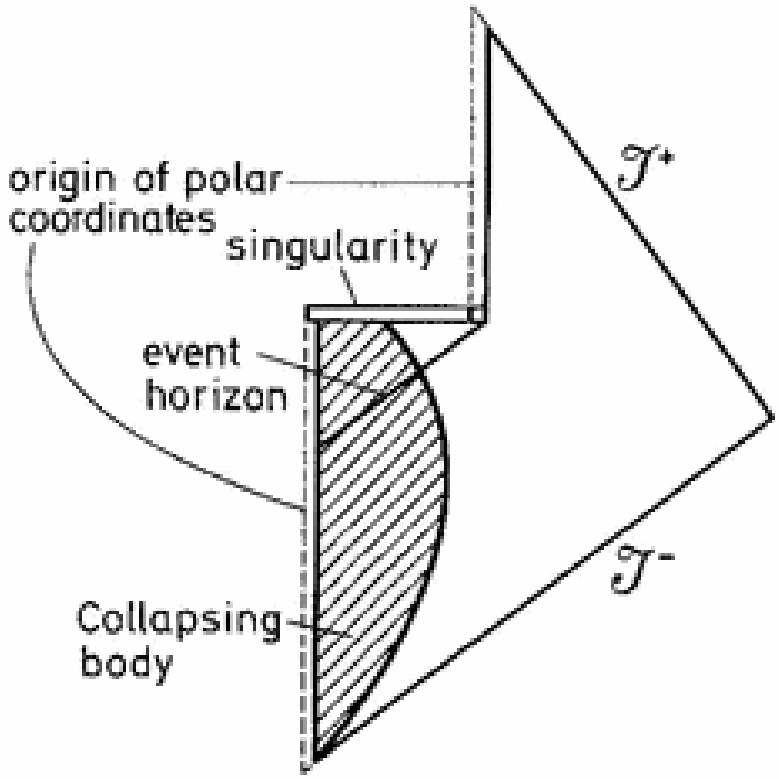
  - Exact black body thermal state (Wald 1975)

Hawking 1976: information loss

- $\psi \in \mathcal{H}_{int} \otimes \mathcal{H}_{ext}$
- $\rho_{ext} = \mathrm{Tr}_{\mathcal{H}_{int}} |\psi\rangle\langle\psi| = \sum p |\phi_{ext}\rangle\langle\phi_{ext}|$
- Pure → Mixed state

- Infalling vs.

  External observer



Early responses

- Prevalence of GR principles?

"[The] event horizon prevents observers at infinity to measure the internal state of the black hole apart from *M*, *Q*, and *J*. This is a quantum version of the no hair theorem" (Hawking 1976)

- Much work on QFT in curved spaces (Unruh, Davies et al.)
- Citation analysis: QFT & GR communities

Early responses (pre-1982)

- On BH evaporation: “I still had to train more in QFT before I could form an informed judgment. Never worked so hard again and never been captivated by a subject as much!” (Wald 2012)

- “The information paradox was not a meteorite hitting the earth. Rather: a bunch of participants developing a story” (Unruh 2012)

- “When I heard Hawking’s info loss result, I thought, ‘Wow! Neat!’ Quickly accepted by the dozen or so GR people who mattered.” (Wald 2012)

- “Created no waves among particle physicists. I did not know about it” (’t Hooft 2012)

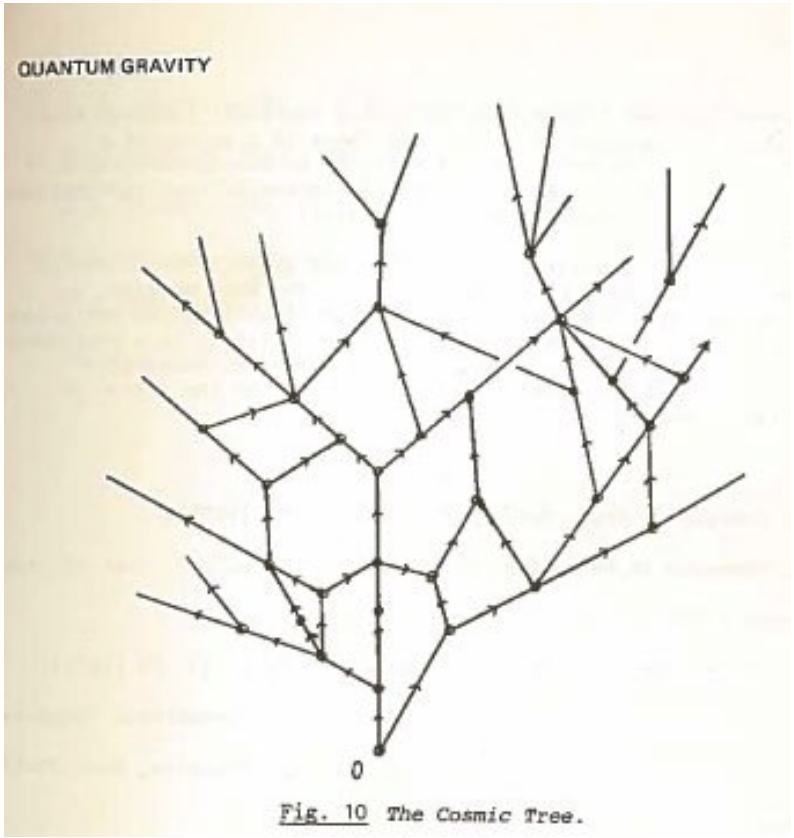


Fig. 10 The Cosmic Tree.

--Renormalization & *Constructive approach with spin lattices*

--'t Hooft: Cargese 78: Hawking's Euclidean path integral derivation

-- Rejected paper with factor 2; 1977-78? Meeting Hawking, Cambridge 1977

Late 70s QG: disparate fields

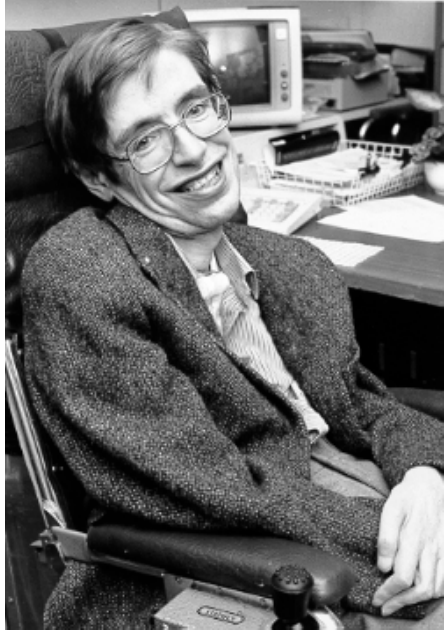
- Meetings across fields? Discussions? Unruh: “No. Particle physicists were not interested in gravity from the 1930s through the 1970s.”

- ’t Hooft (2012): “QG struck me as highly esoteric. No observations; what on earth are all those people doing?”

- “Relativists protested the way I treated [the metric in renormalization study]. The metric was absolutely sacrosanct! Particle physicists feel that way about Hilbert spaces.”

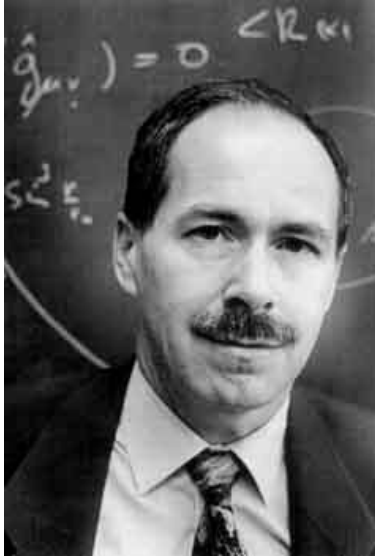
- “We had two different ways of looking at reality and were not yet ready to look at how descriptions could fit together and what questions you could try and solve together. Communication across fields is difficult in physics. How can you make clear that two approaches that look different, that use different words and expressions, address the same problem?”

Early 1980s: particle physicists



- Unruh: “Suddenly these particle physicists turned up and there was a problem. I still don’t get what was so problematic.”
- Hawking 1982 paper?
- Susskind (2008): 1981 EST meeting; ’t Hooft unsure: earlier history with 84 paper: 70s conferences
- Susskind: Particle physicists uninterested. “Complacency bothered me. Great problem of our generation!”
- ’t Hooft (2012) “My reaction was: [non-unitary evolution] is impossible. A black hole is just like other objects. Like a bucket of water. Hawking laughed at the contradictions with QFT: ‘Then you guys are wrong!’ He really thinks in terms of classical relativistic terms: spaces, wormholes, etc.”

Susskind and ’t Hooft papers



- 1984, Contradiction with QFT: Banks-Susskind-Peskin argument:

  “‘$-matrix’ gives information loss → generates entropy → generates heat → energy conservation violated”

- 1985, ’t Hooft: ‘*S*-matrix Ansatz’ (‘principle approach’):

  - ❑ “We start with the postulate that there exists an extension of Hilbert space comprising black holes, and that a Hamiltonian can be precisely defined in this Hilbert space […].”
  - ❑ Construct S-matrix, element by element by focusing on horizon interactions *(controversial: particles there?)*

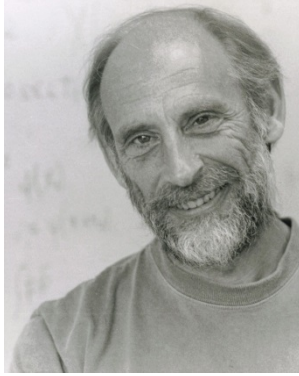
Principle approach

- → 1993: Holography (new principle found!):

  “Given any closed surface, we can represent all that happens inside it by degrees of freedom on this surface itself.”

  “This, one may argue, suggests that quantum gravity should be described entirely by a topological quantum field theory, in which all physical degrees of freedom can be projected onto the boundary.”

1980s: clash without a debate



- Susskind (2008): “All the methodology of particle physics revolves around the […] reversible *S*-matrix. […] All hell would break loose in all of physics, not just black hole physics, once the door to information loss was opened.”

- “Stephen Hawking had put his finger on a *clash of principles*. The Equivalence Principle and Quantum Mechanics were on a collision course.”

- “Only eight journal articles from that entire period address the question of information loss in black holes. I wrote one of them, and ’t Hooft wrote all the rest, largely expressing his faith in the *S*-matrix rather than Hawking’s *$*-matrix.”

- 1988: “I decided that if I couldn’t solve the puzzle, I would become a proselytizer for its importance.”

1980s: Poor communication

- Unruh on BSP: “Simply wrong; complete red herring. BH decoherence does not imply energy non-conservation.” Wald: “Do not disagree with paper, only with its assumptions.” Unruh: “Our [1995] article was completely ignored by particle physicists.”
- Unruh on ’t Hooft: “could not follow those articles at all”

- ’t Hooft: “QG was done from the perspective of either GR or QFT. Between the two was a gap”
- ’t Hooft: “For a while I felt that I stood almost alone. Particle and string theorists were not interested. Thought the black hole was some kind of soliton. None of their business, they thought”

’t Hooft saw plenty of occasions for exchanges, but:

- ’t Hooft & Unruh: “little communication between communities”
- Wald had little cross-disciplinary communication throughout: “Spoken with maybe 6 particle physicists. In [2010] I finally spoke with Banks at Seven Pines” (2012)

- Different in recent ‘firewall’ debate! (Wald 2016)

Early 90s string theory interest: first new calculations

- Susskind: CGHS bh (1+1 dim); BTZ bh (in 2+1 dim, AdS)

- Unruh: New interest in info paradox?? “I did not follow that literature”

- ’t Hooft: “When string theorists finally got started [in 3 + 1 dim] they got it completely wrong. Remnants!”

Key moments according to Susskind

- 1990 “on the radar” & few extra QFT people ’t Hooft-Susskind side

- 1993 BHs are focal point due to CGHS black holes that ‘solve’ info problem

- 1993 BH Complementarity
  - Wald: “Violates local laws of QM. Radical idea to solve a problem I don’t see as radical”
  - Susskind: “Info paradox arrived in a big way”; poll numbers start shifting, reach break even point

- 1993/4: Still not many calculations to do; but also Holography!

Key moments according to Susskind

- 1995 Introduction D-branes
- 1996 Vafa-Strominger calculate extremal bh entropy result (unitary theory!)
- 1996 Callan-Maldacena calculation for near-extremal black holes convinces many senior string theorists : “The jig was up”; paradigm shift inevitable
- 1997 AdS/CFT
- 1998 Witten shows: AdS/CFT is holografic, bh is unitary on boundary: “I knew the bh war was finished”

Ply your trade more profitably?

- ’t Hooft: “My graduate students did not work on the subject because it was difficult to formulate a research question in order to do a proper calculation. That changed with the arrival of string theory interest and D-branes”

- Susskind: Paradigm shift happens when: “1. unexpected exp/math result; 2. technically sophisticated; 3. new ideas provide lots of work for others to do”

Susskind's language

- Martial (*The Black Hole War and My Battle with Steven Hawking to Make the World Safe for Quantum Mechanics*); "neutrals" turned "allies"; and Emotional

- High stakes: "Clash of principles", "Holographic Principle"

- Certain: "[Maldacena and Witten] proved that beyond any shadow of a doubt that information would never be lost"

- But NO deductive certainty: status AdS/CFT, AdS spaces, idealizations and approximations, # of dimensions, etc.

Susskind's language

- Susskind: "*Paradigm shift*"
- "The Black Hole War is over (this claim may upset a handful of people who are still fighting it)"
- "Steven and many in the GR community continued to be blinded by Hawking's early arguments"
- "Hawking had become a tragic figure [who] didn't get the point"
- Holography is now 'normal science'

The role of training

- Susskind: “victims of our faith based illusions? […] It all came down to: which principles do you trust?” [à la Kuhn’s virtues paper] “Hawking was too classically wired”

- ’t Hooft: “Hawking works rather abstractly. Euclidean gravity etc. I like concrete things: particles. Wald, too, is much attached to axiomatic QFT in curved spaces. He really has the relativist’s vision; of people that grew up in GR, have been pampered by GR”

- Who has the proper *authority*?

The role of training (Wheeler)

- Wald: “Most particle physicists are not used to non-Cauchy type evolution laws because they have always worked in flat spacetime. They do not start with a spacetime point of view, but it is awfully difficult to understand a black hole if you do not have a spacetime point of view”

- Unruh: “Particle physicists’ training is strongly rooted in flat spacetime (no singularities, or issues with causality). Unitarity was hammered into them by their professors, so that they stopped thinking about it. Their thought processes are really all stuck down there in flat spacetime”

Today

- Small minority of hold outs; the rest (GR) has moved on. String theorists feel vanquished (AdS/CFT); Firewall debate
- Susskind: Satisfied. “The Holographic Principle” is not speculative anymore, but tool!
- Unruh on AdS/CFT: “I distrust the argument. Can I point to anything? No. I don’t understand string theory well enough.”
- Wald on AdS/CFT: “It is completely unsatisfactory with regards to providing an explanation as to how things work locally.”

Today

- ’t Hooft: Importance of thermodynamic-entropic perspective:
  - “Verlinde has found part of the truth. A black hole is simply the macroscopic limit of something less exotic”
  - However: NO to strings and firewall

- Hawking 2004: conversion.
  - Susskind: somewhat dismissive
  - Unruh: “I was annoyed. Hand waving arguments, following Maldacena, meagre results”
  - Retrained himself in string theory

Paradigm shift?

- Borderline problem produces Anomaly*: the Paradox*
- ‘Trading zone’ but no creole language according to Relativists
- Cultures of theory: the role of pedagogy and practice
- No deductive certainty, despite strong mathematical nature
- Theoreticians’ regress? Calculations *not* too hard to follow

Paradigm shift?

- Paradigm shift but no *Gestalt switches*
- Judging theoretical virtues as values: reweighing of principles in gradual process (not actors mentioned here!) that involved rearrangement of concepts
  - Holography and demotion of spacetime (incommensurability)
  - BH itself moved from soliton/singularity to thermo/stat phys object (idem)

- Tipping point: Ply your trade more profitably in world with Holography
- Continuities too: semiclassical calculation and techniques stayed the same and equally valid (approximative: sufficient or not)
- Allows for hold-outs

‘Acculturation’ of GR’s semiclassical theory in QFT

- QFT now dominant in subject: where does GR find itself?
- Acculturation: integration, separation, marginalization, assimilation
- Hawking’s retraining: ‘integration’? Comes with status loss
- Wald & Unruh: ‘separation’ (“Old guys, that just don’t get it”)
- Communication important: compare ’t Hooft’s and Wald’s comments
- Wald: now “more intermarriage”

HPS and the info paradox: H or P?

- Belot-Earman-Ruetsche (1999) argues that axiomatic QFT in curved spacetimes is fully consistent: hence, pro info loss
- Analysis shows inferences but renders dynamics and today's majority as irrational
- Deductive 'certainty', yet commitment to assumptions of one position!
- Kuhnian weighing of principles and assumptions ('virtues')
- Does that analysis work particularly well due to lack of observation?

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