The Peculiarities of Black Hole Entropy

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[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
"Address to the Mathematical and Physical Sections of the British Association" (1870)

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

What bizarre shit?

– Thomas Pynchon
Gravity's Rainbow
(Tyrone Slothrop, *a.k.a.* Rocketman)

Outline

Mise en scène

Why Black Hole Entropy at All?

What Kind of Entropy?

The Peculiar Modality of Standard Entropy

Physical and Philosophical Musings, with Valediction

Mise en scène

Why Black Hole Entropy at All?

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what is black hole entropy?

$$\frac{A}{4}$$

. . . possibly plus corrections of order $\hbar$

all possibly true. . .

but not illuminating

One who offers clarity and facts but not illumination is insufferable.

– aphorism

why attribute entropy to BHs in the first place, besides formal analogies between laws of ordinary thermodynamics and of BHT?

most initially plausible way to explain what BH entropy measures, and why BHs have such a property in the first place:

Hawking radiation and its well defined temperature
(Sorkin 1998; Preskill 1994)

temperature and entropy go together like Wurst und Senf![1]

or Sturm und Drang?[2]

1. worst en mosterd
2. onweer en aandrang

BUT—no real connection with Hawking radiation/Hawking temperature:

1. some kinds of entropy defined for systems without temperature (*e.g.*, Shannon/information, which many think important here)
2. some kinds defined entirely independent of temperature (*e.g.*, Gibbs)
3. indeed, Hawking radiation is strictly kinematical: needs (essentially) only Lorentz metric with appropriate affine structure and *recherché* properties of quantum-field vacua in CST, nothing to do with dynamics (Visser 1998, 2003; Barceló et al. 2011)...
4. but entropy is fundamentally *dynamical*—that we identify it with *one quarter* the area depends on the form of the EFE (Wald 1993); Hawking radiation/Hawking temperature do not

QG calculations, *e.g.*:

1. Strominger and Vafa (1996) in string theory ("self-intersections of D-branes")
2. Rovelli (1996) in loop quantum gravity ("ensemble/superposition of event horizon states")
3. Dou and Sorkin (2003) in causal set theory ("causal links crossing event horizon")
4. ...

derive $A/4$ from state-counting,
just like in ordinary SM!

Nope! I give arguments against this below, in section "What Kind of Entropy?"

Bekenstein's (1972; 1973; 1974) original motivation:

TO SAVE THE SECOND LAW!

still seems to me the best argument

(briefly: I love me some Second Law, and it had best not be promiscuously violated in any regime that makes non-trivial contact with regimes we've probed, else there would be nothing for it but to collapse in deepest humiliation. . .

but that's another talk entirely)

1. thermodynamical (phenomenological/Clausius)?
2. Boltzmann?
3. Gibbs?
4. von Neumann (entanglement)?
5. Shannon (information)?
6. holographic?
7. something else entirely?

thermodynamical

I claim: there had better be, at least, a good thermodynamical conception

- without a justification and understanding as a truly thermodynamical entropy, no real evidence in first place that BHs have appropriate SM
- string theory, loop quantum gravity, . . . , can count all "micro-states" they want, but we need *independent* reason they're counting *physically relevant* states

(first part of argument why QG calculations can't justify attribution of entropy to BHs) in favor of thermodynamical:

1. GSL (Bekenstein 1972, 1973, 1974)
2. semi-classical BHs support construction of Carnot-like cycles (Kaburaki and Okamoto 1991; Curiel 2014; Bravetti et al. 2016; Prunkl and Timpson 2019)
3. speculative (crazy?) arguments that classical black holes + strictly classical matter jointly have well defined thermodynamics (Curiel 2014 – a few folks like it, including, from time to time, Curiel)

plenty of grounds for questioning, criticizing the last two

SM

but we want SM!

not classical GR, nor even SCG, can alone provide a statistical construction:

- SCG still treats the BH as an entity defined entirely by classical spacetime geometry
- no way to describe such a BH by physical attributes arising as gross statistical measures over underlying, more finely grained quantities
- any statistical accounting, therefore, must come from a theory attributing to classical geometry itself a description based on appropriate micro-structure. . .
- presumably quantum in nature, underlying classical spacetime description of BHs

Boltzmann

a surprisingly common argument for Boltzmann-type (Sorkin 1983; Preskill 1994):[3]

1. Planck length + distinguished geometry provide natural coarse-graining: cover event horizon with Planck-area tiles
2. the horizon then carries some kind of information with density approximately one bit (0/1) per unit area
3. total number of configurations of the order of $N \approx 2^A \Rightarrow S := \log N \approx A \log 2$
4. *voilà!*

3. accident that same folks make this argument as claim Hawking radiation justifies interpretation of BH entropy?

virtues:

1. minimal physical assumptions
2. largely independent of details of any theory of QG

nonetheless, I think this is a crappy argument:

- what is the yes-no question?
- either not counting micro-states relevant to *dynamics* in any straightforward way
- or else *strong* and *unwarranted* assumption that fundamental degrees of freedom are binary (or at least strictly and uniformly bounded by a very small number)
- and, if latter, then *strong* and *unwarranted* assumption that such degrees of freedom can couple in right way with "higher level" degrees of freedom of ordinary matter, *viz.*, QFs (do they give rise to classical spacetime affine structure and how it guides matter evolution? related to Page-time problem)

I have similar problems with many Boltzmannian "state-counting" arguments in weak-regime quantum gravity calculations

- Strominger and Vafa (1996) in string theory ("self-intersections of D-branes")
- Rovelli (1996) in loop quantum gravity ("ensemble of event horizon states")
- Dou and Sorkin (2003) in causal set theory ("causal links crossing event horizon")
- ...

begs the question by *assuming*:

1. that they are counting the dynamically relevant states,
2. that such degrees of freedom can couple in right way with ordinary gross matter
3. *and* that counting measure over states is the appropriate measure—but counting measure is almost never correct in SM

(second part of argument why QG calculations can't justify attribution of entropy to BHs)

Gibbs

I know of no arguments for or against Gibbs in the literature

to move beyond thermodynamical entropy in current epistemic state, I think Gibbs is most promising:

1. almost all proofs of GSL use it (only one I know that doesn't is 2-d string theory – so I'm unimpressed)
2. Gibbsian statistical mechanics is what one wants exactly when no secure knowledge of micro-degrees of freedom and micro-dynamics, only that system couples thermally to external systems
3. avoids Boltzmann worries about latching onto "right" physical micro-degrees of freedom/dynamics

entanglement entropy

"BH entropy proportional to accounting of cross-horizon quantum field entanglement correlations" (Sorkin 1983)

virtues:

- supports derivation of SCEFE (Jacobson 2016)

demerits:

- species problem
- how can it explain increase in entropy when a classical entropic object, like Wheeler's infamous cup of tea, falls into BH?
- how can entanglement correlations across the horizon be sensitive in the right way to the cup's mass and *only* its mass?
- $\Rightarrow$ absolutely no reason for it to show up at the classical level in the Area Theorem (pure differential geometry)
- it may be that as area increases then entanglement entropy increases, but there is no reason to suspect the converse, and *that* is the relevant issue
- entanglement itself has *deep*, unresolved conceptual and foundational problems (Earman 2015)

holographic

"area of privileged null or spacelike surface in bulk proportional to von Neumann entropy of CFT on boundary" (Ryu and Takayanagi 2006; Hubeny et al. 2007; Engelhardt and Wall 2015)

virtues:

- cool and exciting

demerits:

- potentially compelling derivations only in non-physical spacetimes
- reasons to think no derivations in physically relevant spacetimes
- holography has even less epistemic warrant, and we lack even more epistemic control over it, than most things in SCG

something else entirely?

exotica, championed by small but vocal minorities:

1. Barrow entropy
2. Kaniadakis entropy
3. Rényi entropy
4. Sharma-Mittal entropy
5. Tsallis entropy
6. ...

beyond the scope of this talk

entropy is weird

- almost every physical theory defines (or at least admits) an entropy
- in every one, with a single intriguing exception, entropy is fundamentally modal
- thus, several traditional—and hitherto intractable—problems become yet more poignant and difficult, *e.g.*
  - relation to arrow of time
  - interpretation of the Second Law
- recognition points to new avenues of attack on old problems? or further reason for despair?

what I mean when I say "entropy is modal":

1. the definition derives from a principle that itself is modal in character: phenomenological entropy from Clausius and Kelvin Postulates
2. OR the quantity is not intrinsic property of single state, but counterfactual measure of how state would change were it transformed into standard reference state: Clausius entropy
3. OR the quantity is not intrinsic property of single state, but property of modally characterized class of states: Boltzmann entropy
4. OR the quantity is not intrinsic property of single system, but is property of modally characterized class of systems: Gibbs entropy
5. OR not a quantity at all, but a measure of or constraint on various kinds of possibilities, *e.g.*, dynamically possible transitions between states, possible states a system may be in other than its actual one, possible ways a system may be distinguished from, interact with or otherwise be qualified or constrained by its environment, *etc.*: von Neumann entropy

(I do not understand the relations among these conditions, if any) intimately related:

1. entropy mediates no physical coupling between physical systems—only physical quantity I know of that doesn't[4]

2. $\Rightarrow$ *no such thing as an entropometer*

3. exemplification: von Neumann entropy in QM/QFT *is not a quantity associated with the system* (self-adjoint operator)

4. Except time—another tantalizing, possibly deep connection between entropy and time?

semi-classical black holes

$$S = \frac{A}{4}$$

- intrinsic property of single state of individual system
- no arguments needed for natural zero-point
- no counterfactuals, not probabilistic
- physical significance fixed by non-modal principles (First Law, Area Law, Generalized Second Law)
- $\Rightarrow$ *BH entropy is not modal!*
- AND *there is an entropometer!* (doesn't automatically follow from actuality)

questions

1. many different entropies: how do they relate to each other? must we pick one as The One and True Black Hole Entropy?
2. how to interpret identity claims about BH entropy and ordinary entropy?
3. disanalogies with ordinary entropy—virtue or demerit?

a sampling of problems I leave aside (ask in Q&A?):

1. what may this all say about the nature of spacetime and matter, and their interrelations? tune in for my talk here in Utrecht in January!
2. $A/4$ requires prescience?
3. the enormity and discontinuity of $A/4$: why? who? when? where? which? what? whether? withal?
4. physical relations with entropy of ordinary matter (classical and quantum)—fungibility, (sub-)dominance, bounds, *etc.*?
5. physical and conceptual relations with energetic quantities of BHs and ordinary matter?
6. why no significant results in AQFT-CST?
7. why demand that BH SM calculations rely on QSM (QG degrees of freedom)?
8. all QG programs derive $A/4$: trivalizes the evidential power of derivations? (*a.k.a.*: "The 'I'm Always Right' Problem")

many entropies

1. there are many entropy-like quantities one can associate with a BH in many different contexts, under many different representations, depending, *inter alia*, on choice of:[5]
   - type (Clausius, Gibbs, . . .)
   - horizon/surface (event, apparent, quasi-local, isolated, dynamical, QES, . . .)
   - further spacetime structure (asymptotics, symmetries, topology, . . .)
   - dynamical regime (stationary, quasi-stationary, quasi-steady, adiabatic, . . .)
   - energy conditions, entropy bounds
   - *et al.*
2. there is no *a priori* reason to think that exactly one of them is The One and True Black Hole Entropy (Aristotelian essentialism)
3. we are latching on to different, albeit similar things, things which may, in classical contexts, be identified (though often not), but here definitely should not be until further argument is given

5. Wald (1976), Wilkins (1979), Bekenstein (1996), Jacobson et al. (2005), Sorkin (2005), Wall (2009), Carlip (2014), Engelhardt and Wall (2018), and Jacobson (2020)

all made more poignant by fact that everyone and their mother formulates GSL using different types of entropy for, respectively, BH and matter (when they bother to specify at all!)

interpretation

- how can physical quantity with properties as *prima facie* different from ordinary entropy as spatial area be *identical* with it?
- what is criterion for and meaning of identity claim?
- all depends on one's view of inter-theoretic relations (Curiel 2025)

I tentatively favor: do the two properties play the same roles in formulating analogous general principles, and in characterizing interactions between the analogous kinds of systems?

disanalogies

1. not modal; relatedly: entropometer!; and has natural zero-point, unlike entropy for other classical systems
2. scales with square of mass, not linearly (even worse in AdS)
3. isentropic does not imply reversible
4. no Clausius and Kelvin Postulates
5. every other kind of physical system: possible to decrease entropy by throwing in mass-energy; not BHs
6. seems no way to decrease entropy of one BH while increasing that of another, when they interact as a joint system
7. no way to split and recombine a BH isentropically at macro level (“composition of systems”)

but, perhaps we can mitigate identity and modality problems:

- think of area as like volume of hunk of copper under given conditions in ordinary thermodynamics: entropy isn't volume, but is proportional to volume
- then BH entropy is modal in same way: area isn't *identified* with entropy, but rather a measure of some underlying statistical quantity that "really is" entropy
- evidence that BH entropy must have statistical underpinning?
- or just begging the questions?

in any event. . . :

- can disanalogies teach us something about form of possible SM to ground BH entropy (virtue)?[6]
- or militate against interpreting $A/4$ as physical entropy (demerit)?
- differences strongly suggest that extension of entropy to BHs, if correct, should modify and enrich understanding of entropy as physical quantity
- ALSO for temperature and heat (and so Clausius and Kelvin Postulates for BHs?)
- $\Rightarrow$ analogous to how extension of those classical quantities to Maxwell fields did at end of 19th century

6. But see Bardeen (2020) and Frolov (2020).

recall, however, the talk's epigraph from Maxwell: what we are doing here is exactly *not* approaching the questions

> *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.*

for our minds have *NOT* been trained by external nature for studying these phenomena!

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prescience?

1. in order to know current location, and so size, of standard event horizon, one needs to know its entire future
2. $\Rightarrow S_B$ cannot be a well defined state function on a phase space for most commonly used BH models

the enormity and discontinuity of $A/4$

entropy of solar-mass BH $\sim 10^{20}$ larger than Hydrogen gas cloud of same mass

- why—*how*—does the entropy in the relevant spacetime region jump discontinuously by such a Gargantuan amount?
- since standard event horizon is global (prescience), how does the world restricted to a spacelike hypersurface *know* that it has formed?
- could enormously greater values of entropy for systems dominated by gravitational interaction have its roots in the fact that gravity is significantly weaker as a force than the other three?
- perhaps: on account of this weakness, phase-space regions representing system as having larger momentum could be more easily accessible

AQFT-CST?

why no significant results? only recently, and those only for highly specialized spacetimes and matter states, or derivations of quantities not quite Bekenstein entropy:

1. Hollands and Ishibashi (2019)
2. D'Angelo (2021)
3. Kurpicz et al. (2021)

necessity of QSM?

- SM entropy of ordinary systems calculated using "classical particles" or, at most, "non-relativistic qm particles" (*e.g.*, asphalt heating from Sun's blackbody radiation), never from QFT
- in any event, even if we tried to use an SM based on QFT to calculate entropy of air in room, we couldn't do it without making approximations and idealizations that would essentially make all degrees of freedom "localized into something like classical/quantum particles" anyway
- why do—ought—BHs differ in this regard?

triviality of QG?

- essentially every QG program, no matter how different, claims to have derived Bekenstein entropy...
- does it then depend on something that is not peculiar to any particular quantum gravity program?
- if so, then such derivations cannot provide *any confirmation* to any QG program
- indeed, it seems to become even weaker than a minimal consistency requirement