Considering information-theoretic and analogical reasoning in black-hole physics

Christian Wüthrich

Seven Pines Symposium XXI
Black Holes in the Spotlight

20 May 2017

An unusual consensus

- radical divergence about goals, methods, and background we assume fixed in our attempts to formulate, evaluate, and confirm theories of QG
- yet: prima facie surprising agreement of the validity of the Bekenstein-Hawking entropy formula for black holes
- robustness of consensus is curious, as no empirical signatures of Bekenstein entropy are available

Plan

- Revisit Bekenstein's original argument that led him to postulate the existence of a black hole entropy and its proportionality to the hole's area.
- Consider recent analogical reasoning in support of the existence of Hawking radiation in black holes.

Christian Wüthrich. Are black holes about information?. Written for Richard Dawid, Radin Dardashti, and Karim Thébault (editors), *Why Trust a Theory*, Cambridge University Press.

The motivation: the Generalized Second Law

Jacob D Bekenstein. Black holes and the second law. *Lettere al Nuovo Cimento* **4** (1972): 737-740.

Jacob D Bekenstein. Black holes and entropy. *Physical Review* D**7** (1973): 2333-2346.

Bekenstein (1972): Black hole physics potentially violates the Second Law for a package of entropy lowered into a black hole (BH), as once this has settled into equilibrium,

> *...there is no way for the [exterior] observer to determine its interior entropy. Therefore, he cannot exclude the possibility that the total entropy of the universe may have decreased in the process... The introduction of a black-hole entropy is necessitated by [this] process. (737f)*

The motivation: the Generalized Second Law

Law (Generalized Second Law)

"The common entropy in the black-hole exterior plus the black-hole entropy never decreases." (1973, 2339, emphasis in original)

$\Rightarrow$ BH entropy introduced entirely to save (a generalized version of) the second law

- Remark: But of course, the second law is not an exceptionless universal statement, and so may in fact be violated e.g. when BHs are involved.

The solution: the area theorem

Robert M Wald. *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics*. University of Chicago Press, 1994. Chapter 6.

Theorem (Area theorem (Hawking 1970))

For a predictable black hole satisfying $R_{ab}k^a k^b \geq 0$ for all null k^a, the surface area of the future event horizon, h^+, never decreases with time. (Wald, 138)

The structure of the argument:
The analogy to thermodynamic entropy

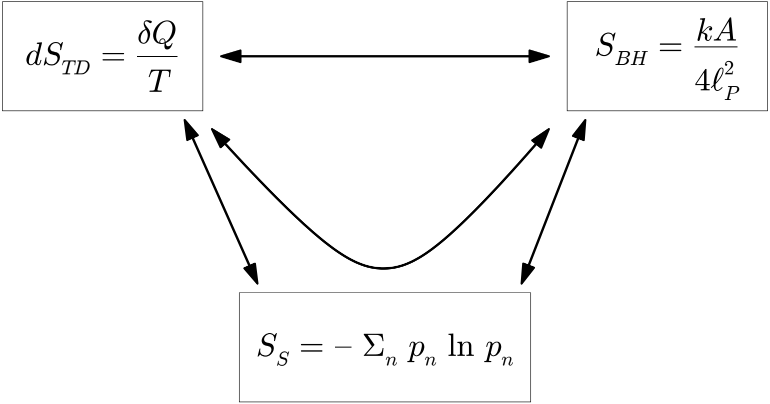
$$dS_{TD} = \frac{\delta Q}{T} \quad \longleftrightarrow \quad S_{BH} = \frac{kA}{4\ell_P^2}$$

The structure of the argument:

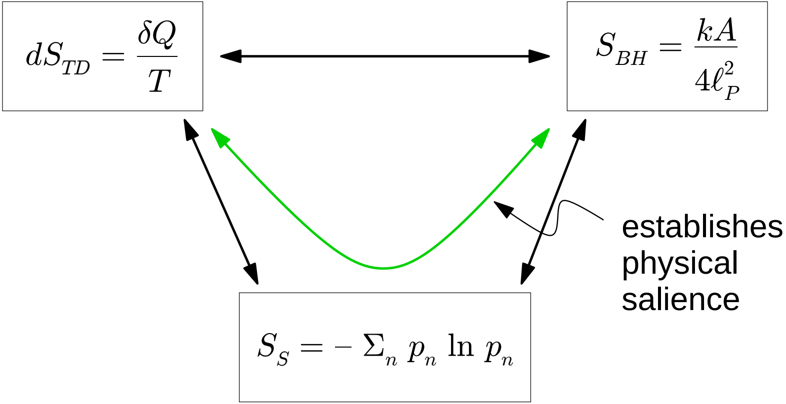
The analogy to thermodynamic entropy: the weak formal analogy

$$dS_{TD} = \frac{\delta Q}{T} \longleftrightarrow S_{BH} = \frac{kA}{4\ell_P^2}$$

The structure of the argument:
Bekenstein's intention



The structure of the argument:
Bekenstein's intention



The structure of the argument:
E. T. Jaynes's (and L. Brillouin's) identification

$$S_G = -k\,\Sigma_i\, p_i \log p_i$$

$$\updownarrow$$

$$S_S = -\Sigma_n\, p_n \ln p_n$$

The structure of the argument:
Bekenstein's endorsement of the Jaynesian identification

The entropy of a system measures one's uncertainty or lack of information about the actual internal configuration of the system... The second law of thermodynamics is easily understood in the context of information theory... (1973, 2335)

The structure of the argument:
Bekenstein's identification

$$S_{BH} = \frac{kA}{4\ell_P^2}$$

$$S_S = -\Sigma_n \, p_n \ln p_n$$

The structure of the argument:
Bekenstein's identification

PHYSICAL REVIEW D VOLUME 7, NUMBER 8 15 APRIL 1973

Black Holes and Entropy*

Jacob D. Bekenstein†
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
and Center for Relativity Theory, The University of Texas at Austin, Austin, Texas 78712‡
(Received 2 November 1972)

There are a number of similarities between black-hole physics and thermodynamics. Most striking is the similarity in the behaviors of black-hole area and of entropy: Both quantities tend to increase irreversibly. In this paper we make this similarity the basis of a thermodynamic approach to black-hole physics. After a brief review of the elements of the theory of information, we discuss black-hole physics from the point of view of information theory. We show that it is natural to introduce the concept of black-hole entropy as the measure of information about a black-hole interior which is inaccessible to an exterior observer. Considerations of simplicity and consistency, and dimensional arguments indicate that the black-hole entropy is equal to the ratio of the black-hole area to the square of the Planck length times a dimensionless constant of order unity. A different approach making use of the specific properties of Kerr black holes and of concepts from information theory leads to the same conclusion, and suggests a definite value for the constant. The physical content of the concept of black-hole entropy derives from the following generalized version of the second law: When common entropy goes down a black hole, the common entropy in the black-hole exterior plus the black-hole entropy never decreases. The validity of this version of the second law is supported by an argument from information theory as well as by several examples.

The structure of the argument:
Bekenstein's identification

In the context of information a black hole is very much like a thermodynamic system... Black holes in equilibrium having the same set of three parameters may still have different 'internal configurations'... It is then natural to introduce the concept of black-hole entropy as the measure of the inaccessibility of information (to the exterior observer) as to which particular internal configuration of the black hole is actually realized in a given case.

At the outset it should be clear that the black-hole entropy we are speaking of is not the thermal entropy inside the black hole. (1973, 2336, emphases in original)

The structure of the argument:
Bekenstein's identification broken

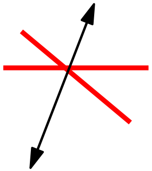
- Why think that entropy package that crosses the horizon no longer has sufficient entropy to uphold Second Law?
- Alternatively: take perspective of external observer seriously; but they never see the package vanish behind the event horizon!
- Generally speaking, fundamental physics is about objective structure of our world, not about our beliefs or our information or about our epistemic status

$\Rightarrow$ Do not conflate epistemology and ontology!

- Against hyper-pythagoreanism: fundamental physics not "in context of information", not about abstracta

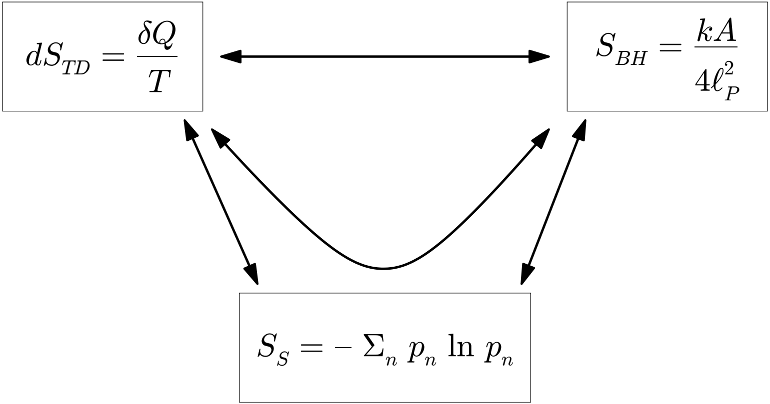
The structure of the argument:
Bekenstein's identification broken

$$S_{BH} = \frac{kA}{4\ell_P^2}$$

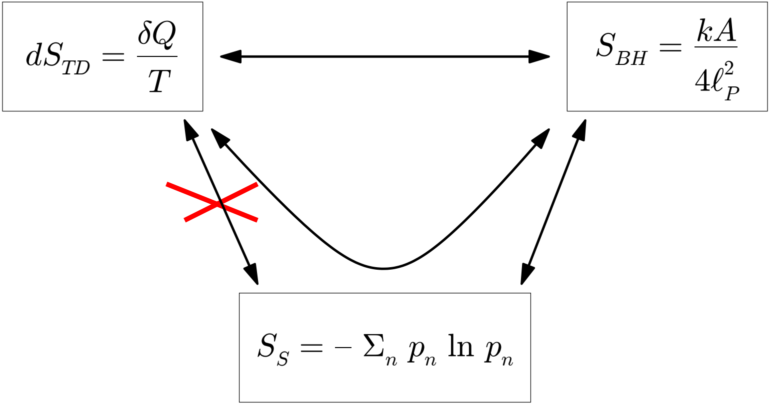


$$S_S = -\sum_n p_n \ln p_n$$

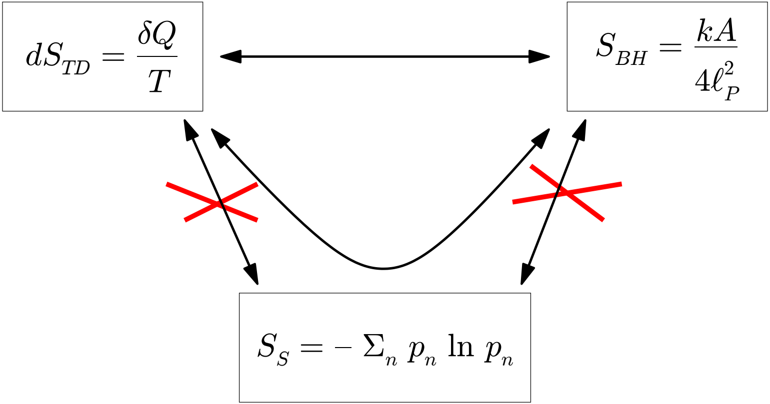
Back to the overall structure of the argument



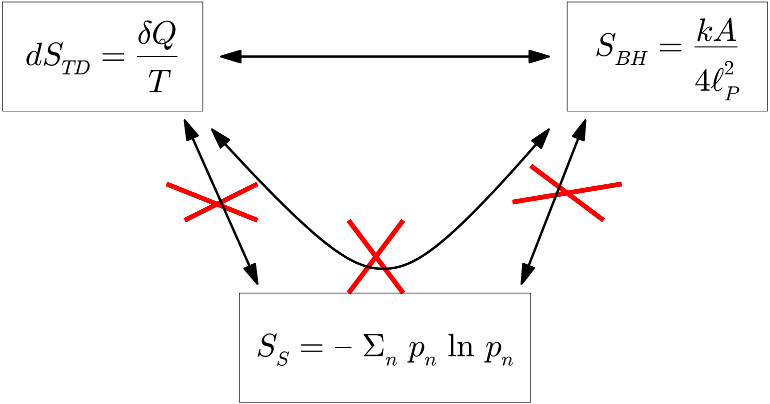
Back to the overall structure of the argument



Back to the overall structure of the argument



Back to the overall structure of the argument



Back to the weak formal analogy?

$$dS_{TD} = \frac{\delta Q}{T} \quad \longleftrightarrow \quad S_{BH} = \frac{kA}{4\ell_P^2}$$

Intermediate conclusion

- If the detour through information theory does not succeed, then the argument fails to establish the physical salience of the otherwise merely formal analogy between thermodynamic entropy and the black hole area. But...

Hawking radiation

- Sorkin (1998): Hawking radiation is "best known piece of evidence" for the association between horizon area with entropy
- In fact, most physicists did not take Bekenstein's argument seriously: classical black holes do not radiate, so have no temperature, and so are not thermodynamic anyway.
- This changes at once when Hawking put forth his semi-classical argument to show that black holes radiate...
- So, the (direct or indirect) empirical confirmation of Hawking radiation would strongly support the idea.

Stephen W Hawking. Particle creation by black holes. *Communications in Mathematical Physics* **43** (1975): 199-220.

Rafael Sorkin. The statistical mechanics of black hole thermodynamics. In R Wald (ed.), *Black Holes and Relativistic Stars*. University of Chicago Press, 1998, pp. 177-194.

Analogue gravity to the rescue?

- Problem: Hawking radiation of black holes not detectable in practice

⇒ study 'analogue' systems, such as sound in fluid (Unruh 1981)

- (Unreproduced) observation of Hawking radiation in analogue systems, such as Bose-Einstein condensates (Steinhauer 2016)

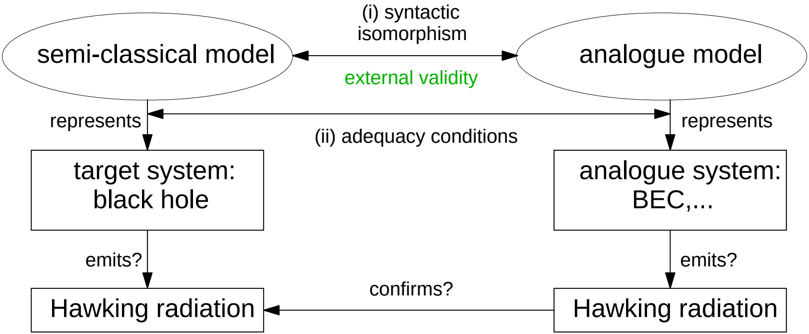
William G Unruh. Experimental black-hole evaporation?. *Physical Review Letters* **46** (1981): 1351-1353.

Jeff Steinhauer. Observation of quantum Hawking radiation and its entanglement in an analogue black hole. *Nature Physics* **12** (2016): 959-965.

Basic idea: If two systems are known to be similar in some relevant respects, then we are justified in thinking that they are also similar in some unknown respects.

Confirmation via analogue simulation

Radin Dardashti, Karim P Y Thébault, Eric Winsberg. Confirmation via analogue simulation: what dumb holes could tell us about gravity. *British Journal for the Philosophy of Science* **68** (2017). 55-89.



Conditions underwriting universality claim

1. Two generally necessary conditions to reproduce Hawking radiation, and so for external validity to a more general class of target systems to hold (Barcelo et al 2011):
    - form of quantum analogue model: relativistic quantum fields on classical effective background spacetime
    - horizon is present in geometry of model
2. necessary conditions for the universality claim by Unruh and Schützhold (2005)—solving the trans-Planckian problem—to obtain (Dardashti et al, 81):
    - breakdown of geometric optics in vicinity of horizon only
    - There is a privileged, freely falling frame.
    - Planckian modes start off in ground state
    - evolution of modes is adiabatic

Worry: are we begging the question?

- Goal: to establish that black holes are thermodynamic objects, as firm stepping stone to a theory of quantum gravity; emitting radiation would be strong indication that they are
- If detection of radiation is indirect through "analogue simulation", external validity must be ascertained.
- For this, we need to know whether the conditions underwriting external validity are in place.
- And for this, we ultimately need a fundamental theory from which the relevant physics is derived in appropriate approximations.

Disanalogy: whereas in the analogue cases, we have such fundamental theories (molecular hydrodynamics, Bogoliubov BEC, ultimately QFT), but of course we don't have that in case of quantum gravity...

Conclusions

- Black holes may well turn out to be thermodynamic objects.
- Establishing that they are, however, is far from trivial: many arguments are suggestive, but not conclusive, and should be treated accordingly.
- Eventually, nothing can give us firmer constraints on theorizing in quantum gravity than directly relevant empirical work, such as the observation of black holes or other astrophysical objects.
- Let's do astronomy and quantum gravity phenomenology!

Bekenstein's reasoning

1. The universe as a whole has an entropy.
2. The Second Law is a universal law, i.e., applies to the universe as a whole; in particular (a generalization of) it still obtains in the presence of black holes.
3. The Second Law can only hold in the presence of black holes if the black holes present have an entropy contributing to the total entropy of the universe.
4. The area of the event horizon of a black hole is the only property of a black hole which is formally similar to ordinary thermodynamic entropy in that it both tends to increase over time.

Bekenstein's reasoning

5. The horizon area of a black hole is essentially the same kind of physical quantity as information-theoretic entropy.
6. Information-theoretic entropy is essentially the same kind of physical quantity as ordinary thermodynamic entropy.
7. Therefore, the horizon area of a black hole and ordinary thermodynamic entropy are essentially the same kind of physical quantity (which explains their formal similarity).
8. Therefore, black holes have an entropy contributing to the total entropy of the universe.
9. Therefore, (a generalization of) the Second Law still obtains in the presence of black holes.