nature astronomy

PERSPECTIVE

https://doi.org/10.1038/s41550-018-0602-1

The many definitions of a black hole

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Although black holes are objects of central importance across many fields of physics, there is no agreed upon definition for them, a fact that does not seem to be widely recognized. Physicists in different fields conceive of and reason about them in radically different, and often conflicting, ways. All those ways, however, seem sound in the relevant contexts. After examining and comparing many of the definitions used in practice, I consider the problems that the lack of a universally accepted definition leads to, and discuss whether one is in fact needed for progress in the physics of black holes. I conclude that, within reasonable bounds, the profusion of different definitions is in fact a virtue, making the investigation of black holes possible and fruitful in all the many different kinds of problems about them that physicists consider, although one must take care in trying to translate results between fields.

What is a black hole? That may seem an odd question. Given the centrality of black holes to theoretical work across many fields of physics today, how can there be any uncertainty about it? Black holes (and their analogues) are objects of theoretical study in almost everything from optics to solid-state to superfluids to ordinary hydrodynamics and thermodynamics to high-energy particle physics to astrophysics to cosmology to classical, semi-classical and quantum gravity; and of course they are central subjects of observational work in much of astronomy. That fact perhaps provides part of the answer about the uncertainty: there is not so much uncertainty about a single, canonical answer, but rather there are too many good possible answers to the question, not all consistent with each other. That is what makes the question of interest. There is likely no other physical system of fundamental importance about which so many different answers are to be had for its definition, and so many reasons to be both satisfied and dissatisfied with all of them. Beatrice Bonga, a theoretical physicist, summed up the situation admirably (personal communication): "Your five word question is surprisingly difficult to answer … and I definitely won't be able to do that in five words." (From hereon, when I quote someone without giving a citation, it should be understood that the source is personal communication.)

The question is not only interesting (and difficult) in its own right. It is also important, both for practical reasons and for foundational ones. The fact that there are so many potentially good answers to it, and seemingly little recognition across the fields that each relies on its own peculiar definition (or small set of definitions), leads to confusion in practice. Indeed, I first began to think deeply about the question when I noticed, time and again, disagreements between physicists about what to my mind should have been basic points about black holes all would agree on. I subsequently traced the root of the disagreements to the fact that the physicists, generally from different fields (or even only different subfields within the same field, such as different approaches to quantum field theory on curved spacetime), were implicitly using their own definition of a black hole, which did not square easily with that of the others in the conversation. Different communities in physics simply talk past each other, with all the attendant difficulties when they try to make fruitful contact with one another, whether it be for the purposes of exploratory theoretical work, of concrete observational work, or of foundational investigations. (Ashtekar and Krishnan[1], in a review of work on isolated horizons, give the only discussion I know of in the literature on this exact issue, that different fields of physics use different definitions and conceptions of a black hole.)

The profusion of possible definitions raises problems that are especially acute for foundational work. The ground-breaking work of Hawking[2,3] concluded that, when quantum effects are taken into account, black holes should emit thermalized radiation like an ordinary blackbody. This appears to point to a deep and hitherto unsuspected connection among our three most fundamental, deeply entrenched theories: general relativity, quantum field theory, and thermodynamics. Indeed, black hole thermodynamics and results concerning quantum fields in the presence of strong gravitational fields more generally are without a doubt the most widely accepted, most deeply trusted set of conclusions in theoretical physics in which those theories work together in seemingly fruitful harmony.

All is not as rosy, however, as that picture may paint it. The deep trust in results about black hole thermodynamics is 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. Those results, moreover, come from taking two theories (general relativity and quantum field theory)—each of which is in manifest conceptual and physical tension with the other in a variety of respects, and each of which is more or less well understood and supported in its own physical regime radically separated from that of the other—and attempting to combine them in novel ways guided by little more than physical intuition (which differs greatly from physicist to physicist) and then extending that combination into regimes we have no hard empirical knowledge of whatsoever. It is far from clear, however, among many other issues, what it may mean to attribute thermodynamic properties to black holes[4]. The problem is made even more acute when one recognizes that this attribution suffers by necessity from the same ambiguity as the idea of a black hole itself. Attempts to confront such fundamental problems as the information-loss paradox[5,6] are in the same boat. Since almost everyone agrees that black hole thermodynamics provides our best guide for clues to a successful theory of quantum gravity, it would be useful to know what exactly those clues are. Thus, it behooves us to try to get clear on what black holes are.

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I shall speak in this Perspective as though the task is to provide a definition, in perhaps something like a logical sense, for black holes. In their daily practice, I suspect most physicists do not think in those terms, having rather more or less roughly delineated conceptions—a picture of what they mean by 'black hole'—they rely on in their work. Nonetheless, for ease of exposition, I will continue to speak of definitions.

The history

In the 1960s, our understanding of general relativity as a theory experienced a revolution at the hands of Penrose, Hawking, Geroch, Israel, Carter and others, with the development of novel techniques in differential topology and geometry to characterize the global structure of relativistic spacetimes in ways not tied to the specifics of particular solutions and independent of the assumption of high degrees of symmetry. This work in part originated with the attempt to understand the formation of singularities and the development of the causal structure of spacetime during the gravitational collapse of massive bodies such as stars. It culminated in the classic definition of a black hole as an event horizon (the boundary of what is visible from, and therefore what can in principle escape to, 'infinity'), the celebrated singularity theorems of Penrose, Hawking, and Geroch, the no-hair theorems of Israel, Carter and others, Penrose's postulation of the cosmic censorship hypothesis, the demonstration that trapped surfaces (close cousins to event horizons) will form under generic conditions during gravitational collapse, and many other results in classical general relativity that today ground and inform every aspect of our understanding of relativistic spacetimes. (For those interested in the fascinating history of the attempts to understand black-hole solutions to the Einstein field equation before the 1960s, see Earman[7], Earman and Eisenstadt[8], and Eisenstadt[9].)

Among the community of physicists steeped in classical general relativity, exemplified by the groups associated with John Wheeler at Princeton and Dennis Sciama at Cambridge, this was heady stuff. According to active participants of those groups at the time, no one in that community had the least doubt about what black holes were and that they existed.

It was otherwise with astrophysics and more traditional cosmology in the 1960s. There was controversy about whether or not to take seriously the idea that black holes were relevant to real-world physics. For many, black holes were just too weird—according to the relativists' definition, a black hole is a global object, requiring that one know the entire structure of spacetime to characterize it (more on this below), not a local object determinable by local observations of phenomena of the sort that are the bread and butter of astrophysics. In his classic text on general relativity and cosmology, Weinberg[10], for instance, strongly suggests that black holes are not relevant to the understanding of compact cosmological objects such as quasars, expresses deep skepticism that real stars will collapse to within their Schwarzschild radius even while citing Penrose on the formation of trapped surfaces, and completely dismisses the idea that the interior of the event horizon of the Schwarzschild black hole is relevant for understanding collapse at all.

One crucial point that astrophysicists and cosmologists of the time were not in a position to recognize, however, because of their conception of black holes as spatially localized, compact objects formed by collapse from which nothing can escape, is that black holes are not associated only with traditional collapse phenomena. As Bob Geroch, a theoretical physicist known for his work in classical general relativity, points out (personal communication), if all the stars in the Milky Way gradually aggregate towards the Galactic Centre while keeping their proportionate distances from each other, they will all fall within their joint Schwarzschild radius long before they are forced to collide. There is, in other words, nothing necessarily unphysical or mysterious about the interior of an event horizon formed from the aggregation of matter. Reasoning such as this based on their definition of a black hole as a spacetime region encompassed by an event horizon confirmed the relativists in their faith in the existence of black holes, confirmation buttressed by the conviction, based on Penrose's results about the formation of trapped surfaces during generic collapse, that the extremity of self-gravitational forces in traditional collapse would overwhelm any possible hydromagnetic or quantum effects resisting it.

This paints the picture with an extremely broad and crude brush, and there were many astrophysicists and cosmologists who did not conform to it. As early as 1964 Edwin Salpeter and Yakov Zel'dovič had independently argued that supermassive black holes accreting gas at the centres of galaxies may be responsible for the enormous amounts of energy emitted by quasars, along with their large observed variability in luminosity. In the early 1970s, Donald Lynden-Bell proposed that there is a supermassive black hole at the centre of the Milky Way. Zel'dovič in Moscow and groups led by Lynden-Bell and by Martin Rees in Cambridge (UK) at the same time independently worked out detailed theoretical models for accretion around black holes for quasars and X-ray binaries.

Based on observational work, astrophysicists knew that some massive, compact object had to be at the centre of a quasar, but there was still reticence to fully embrace the idea that it was a black hole. Accretion onto a black hole was at that point the widely accepted model, to be sure, but the seemingly exotic nature of black holes left many astrophysicists with unease; there was, however, no other plausible candidate known. With upper possible mass limits on neutron stars worked out in the 1970s, and more and more observational evidence coming in through the 1980s that the objects at the centre of quasars had to be more massive than that, and compressed into an extremely small volume, more and more doubters were won over as theoretical models of no other kind of system could so well account for it all. (It is amusing to note, however, that even well into the 1980s Bob Wald, a theoretical physicist at the University of Chicago, had to warn astrophysicists and cosmologists visiting there against describing black holes as 'exotic' in their talks, as that would have led to the interruption of their talk for chastisement by Chandrasekhar.) Cygnus X-1 and other X-ray binaries also provided observational evidence for black holes in the early 1970s. It is perhaps fair to say that the community achieved something like unanimous agreement on the existence and relevance of black holes only in the early 2000s, with the unequivocal demonstration that SgrA*, the centre of the Milky Way, holds a supermassive black hole, based on a decade of infrared observations by Reinhard Genzel, Andreas Eckart, and Andrea Ghez[11,12].

Possible answers

In *Confessions*, Saint Augustine famously remarked: "Quid est ergo tempus? Si nemo ex me quærat, scio; si quærenti explicare velim, nescio." ("What then is time? If no one asks me, I know what it is. If I wish to explain it to someone who asks, I do not know." Lib. XI, Cap. XIV.) As for time, so for black holes. Most physicists, I believe, know what a black hole is, right up until the moment you blindside them with the request for a definition. In preparation for writing this Perspective, I did exactly that. I posed the question, with no warning or context, to physicists both young and old, just starting out and already eminent, theoretician and experimentalist, across a wide variety of fields. The results were startling and eye-opening, not only for the variety of answers I got but even more so for the puzzlement and deep thoughtfulness the question occasioned. Several of the answers I received are collected in Boxes 1, 2 and 3.

I will discuss the possible definitions in detail shortly. Before diving in, however, it will be useful to sketch the terrain in rough outline. In Table 1, I lay out the core concepts that workers in different fields tend to use when thinking about black holes. The table, however, is only a rough guide. As we can see from the quotes from physicists in different fields given in the boxes, and from the more

Table 1 | The core concepts common to different fields for characterizing black holes

Field	Core concepts
Astrophysics	•Compact object •Region of no escape •Engine for enormous power output
Classical relativity	•Causal boundary of the past of future null infinity (event horizon) •Apparent horizon •Quasi-local horizon
Mathematical relativity	•Apparent horizon •Singularity
Semi-classical gravity	•Same as classical relativity •Thermodynamic system of maximal entropy
Quantum gravity	•Particular excitation of quantum field •Ensemble or mixed state of maximal entropy •No good definition to be had
Analogue gravity	•Region of no escape for finite time, or for low energy modes

detailed discussion below, not all physicists in a given field conform to the standard.

Most likely because of my training and the focus of most of my own work in classical general relativity and semi-classical gravity, I naively expected almost everyone I asked at least to mention "the boundary of the causal past of future null infinity", the classic definition of the event horizon dating back to the ground-breaking work of the mid-to-late 1960s, as laid down in the canonical texts on general relativity by Hawking and Ellis[13] and by Wald[14]. In the event, many did not, and most of those who mentioned it did so at least in part to draw attention to its problems. The definition tries to take the intuition that a black hole is a 'region of no escape' and make it precise. In order for the idea of a region of no escape to be cogent, there must be another region stuff possibly could escape to, so long as it never enters the trapping region. The definition thus states in effect that a spacetime has a black hole if one can divide the spacetime into two mutually exclusive, exhaustive regions of the following kinds. The first, the exterior of the black hole, is characterized by the fact that it is causally connected to a region one can think of as being 'infinitely far away' from the interior of the spacetime; anything in that exterior region can, in principle, escape to infinity. The second region, the interior of the black hole, is characterized by the fact that once anything enters it, it must remain there and cannot, not even in principle, escape to infinity, nor even causally interact in any way with anything in the other region. The boundary between these two regions is the event horizon.

This definition is global in a strong and straightforward sense: the idea that nothing can escape the interior of a black hole once it enters makes implicit reference to all future time—the thing can never escape no matter how long it tries. Thus, in order to know the location of the event horizon in spacetime, one must know the entire structure of the spacetime, from start to finish, so to speak, and all the way out to infinity. As a consequence, no local measurements one can make can ever determine the location of an event horizon. That feature is already objectionable to many physicists on philosophical grounds: one cannot operationalize an event horizon in any standard sense of the term. Another disturbing property of the event horizon, arising from its global nature, is that it is prescient. Where I locate the horizon today depends on what I throw in it tomorrow—which future-directed possible paths of particles and light rays can escape to infinity starting today depends on where the horizon will be tomorrow, and so that information must already be accounted for today. Physicists find this feature even more troubling.

> The existence of [a classical event horizon] just doesn't seem to be a verifiable hypothesis.
>
> – Sean Gryb, theoretical physicist
> (shape dynamics, quantum cosmology)

For reasons such as those, some physicists define a black hole as a kind of horizon whose characteristic properties may be relative to a particular set of observers and their investigative purposes, similar to how 'equilibrium' in thermodynamics must be defined for a system with respect to some characteristic time-scale picked out by the physics of the problem at hand. Other physicists propose generalizing the classic definition in other ways that make explicit reference to observers, so-called causal horizons[15]. This allows one to bring the concept of a black hole as a horizon into immediate contact with other more general kinds of horizons that appear in general relativity, in order to formulate and prove propositions of great scope about, say, their thermodynamic properties. It is interesting to note that several of these other conceptions of a horizon do not depend on a notion of infinity in the sense of a place one can unambiguously escape to (null or spatial infinity), but they do still make implicit reference to a future temporal infinity.

Such causal horizons are still global in nature, however, so, in attempting to assuage the general dissatisfaction with the global nature of the classic definition, one possible strategy is to attempt to isolate some characteristic feature of a global black hole that can be determined locally. One popular such feature is a so-called apparent horizon, a structure that generically appears along with a classical event horizon, but whose existence and location can seemingly be determined locally, and which can also be defined in spacetimes in which an event horizon cannot, for example, those that are bounded in space so there is no good notion of 'escape to infinity'. An apparent horizon is a two-dimensional surface (which we may for our purposes think of as a sphere) such that, loosely speaking, all light rays emanating outward from nearby points on its surface start out parallel to each other. This captures the idea that "nothing, not even light, can escape" in a local fashion—outgoing light wants to remain tangent to the surface. Note, however, that there is no guarantee that something entering the region bounded by a suitable characterization of the future evolution of such a surface may not later be able to exit from it.

Many characteristic properties of classical event horizons already follow from the idea of an apparent horizon, and it is easily generalized to alternative theories of gravity (such as non-quantum gravitational theories that differ from general relativity). Nonetheless, apparent horizons (and other such 'local' notions of a horizon, which I discuss briefly below) are not quite so local as commonly held opinion assumes: to determine that a surface is an apparent horizon, one still needs to determine that neighbouring outgoing light rays propagate parallel to each other all at once on the entire surface. No observer could ever determine this in practice, though perhaps a large team of perfectly synchronized observers could do it in principle. An even more serious problem, however, is that apparent horizons are slice-dependent, that is, whether one takes an apparent horizon to be present or not depends on how one foliates spacetime by space-like hypersurfaces—or how one locally splits spacetime up into spatial and temporal parts. Many physicists are uncomfortable with grounding reasoning of a fundamental nature on objects or structures that are not invariantly defined with respect to the full four-dimensional spacetime geometry.

Mathematicians in general are also leery of the global nature of the classic definition. In recent decades, mathematical relativity has largely focused on studying the initial-value problem of general relativity, attempting to characterize solutions to the Einstein field equation viewed as a result of dynamical evolution starting from initial data on three-dimensional space-like hypersurfaces. This initial data determines spacetime structure locally in the domain of evolution. Because the presence of apparent horizons can be determined locally in a mathematically relevant sense, they often use this as the marker that a black hole is present. Under a few seemingly benign assumptions, moreover, the presence of an apparent horizon leads by the classic Penrose singularity theorem[16] to the existence of a singularity one expects to find inside a black hole. Since the presence of a singularity can also be determined locally, it is often included in the definition of a black hole for mathematicians.

The mathematicians' conception does not, however, meet all their own desiderata. First, the initial data is not truly local—one must in general specify conditions on it asymptotically, at 'spatial infinity', and it is difficult at best to see why needing to know the structure of spacetime at "all of space at a given moment of time" is epistemically superior to needing to know the future structure of spacetime. Even worse, it does not suffice for an unambiguous definition of a black hole. We have little understanding of the evolution of generic initial data for the Einstein field equation. We know of no way in general to determine whether a set of locally stipulated initial conditions will eventuate in anything like a classical horizon or singularity, except by explicitly solving the equations, and that is almost never feasible in practice, outside special cases of unrealistically high degrees of symmetry.

> [The classic conception of a horizon] is probably a very useless definition, because it assumes we can compute the future of real black holes, and we cannot.
>
> – Carlo Rovelli, theoretical physicist
> (classical general relativity, loop quantum gravity, cosmology, foundations of quantum mechanics)

Besides the apparent horizon, there are other quasi-local characterizations of black holes that do not have objectionable global features, such as dynamical trapping horizons[17] and isolated horizons[18]. Several physicists and astrophysicists in their replies to me mention these, mainly to discuss their virtues, but they are difficult to describe without resorting to technical machinery. One may usefully think of them as closed surfaces that have many of the properties of apparent horizons, without necessarily being associated with a classical event horizon. They have problems of their own, though, a severe one being that they are slice-dependent in the same way as apparent horizons. Also, perhaps even worse, they have a form of 'clairvoyance': they are aware of and respond to changes in the geometry in spacetime regions that they cannot be in causal contact with[19]. Indeed, they can encompass regions whose entire causal past is flat. This should be at least as troubling as the 'prescience' of global event horizons.

The global and prescient nature of the classical event horizon never bothered me. I see the classic definition as an elegant and powerful idealization, nothing else, allowing us to approximate the spacetime structure around a system that is for all intents and purposes isolated from the rest of the universe in the sense that the gravitational (and other) effects of all other systems are negligible—spacetime in our neighbourhood is approximately flat compared to regions around objects we attempt to study and think of as black holes, and we are very, very far away from them. It is also an idealization that allows us to prove theorems of great depth and scope, giving us unparalleled insight into the conceptual structure of general relativity as a physical theory (in so far as one trusts results based on the idealization to carry over to the real world). This of course still leaves us with the task of characterizing what it means for a region of spacetime to 'act approximately like a black hole' in a way that renders the idealization suitable for our purposes. Given the number of features one may want to take as characteristic and try to hold on to, and the fact that one will not be able to hold on to all of them (as discussed below), this still leaves a great deal of freedom in fleshing out the idea of 'acting approximately like a black hole' as a fruitful conception, and that presumably will again depend on the details of the investigations at hand and the purposes of the physicists engaged in them.

Astrophysicists, in their applied work, tend to be sanguine about the global nature of the classic definition. They are happy to avail themselves of the deep results about horizons that the classic definition allows us to prove when, for example, they try to determine what observable properties a region of spacetime may have that would allow us to conclude that what we are observing is a black hole in their sense. They still use in their ordinary practice, nonetheless, a definition that is tractable for their purposes: a system of at least a minimum mass, spatially small enough that relativistic effects cannot be ignored. Neutron stars cannot have a mass greater than about 3 solar masses, and a star with greater mass will not be relativistic in the relevant sense. It more or less follows from this, as other astrophysicists stress as a characteristic property when defining a black hole, that it be a region of no escape in a sense relevant to their work.

> A black hole is a compact body of mass greater than four solar masses—the physicists have shown us there is nothing else it can be.
>
> – Ramesh Narayan, astrophysicist
> (active galactic nuclei, accretion disk flow)

None of this, however, distinguishes a black hole from a naked singularity (that is, a singularity not hidden behind an event horizon, ruled out by Penrose's cosmic censorship conjecture[20]). Astrophysicists tend to respond to this problem in two ways. First, they try to exclude the possibility of naked singularities on other theoretical grounds; second, much work is currently being done to try to work out properties of naked singularities that would distinguish them observationally from black holes[21]. There are many other fascinating methodological and epistemological problems with trying to ascertain that what we observe astronomically conforms to these sorts of definitions[22,23], but it would take us too far afield to go into them here.

It is worth remarking that it is not only astrophysicists who share this conception. Many theoretical physicists working in programmes from high-energy particle physics to loop quantum gravity also champion definitions that latch on to one facet or another of the standard astrophysics definition. Gerard 't Hooft, for instance, in his remarks quoted in Box 2, emphasizes his conception of a black hole as a vacuum solution resulting from total collapse, adding a subtle twist to the astrophysicist's concrete picture in which ordinary matter may be present (for example, in an accretion disk), a twist perhaps congenial to a particle physicist's aims of investigating the transformations of the vacuum state of a quantum field in the vicinity of a horizon. Others take over the astrophysicist's picture wholesale, emphasizing that previous purely theoretical conceptions are no longer adequate for contemporary work that would make contact with real observations, as Carlo Rovelli makes clear in his remarks quoted above and in Box 1. Nonetheless, as well as the astrophysicist's picture may work in practice, it also faces serious conceptual problems. Black holes simply are not anything like other kinds of astrophysical systems that we study—they are not bits of stuff with well defined spatiotemporal positions that interact with ordinary systems in a variety of ways other than gravity.

In the semi-classical framework, one treats the spacetime geometry as classical, with quantum fields propagating on it as their background. In that picture, some of the concerns just discussed appear to be mitigated. Black holes seem to acquire some of the most fundamental properties of ordinary physical systems: they exhibit

Box 1 | Astrophysical views on black holes

> A black hole is the ultimate prison: once you check in, you can never get out.
>
> –Avi Loeb, astrophysicist
> (cosmology, black hole evolution, first stars)

> For all intents and purposes we *are* at future null infinity with respect to SgrA*.
>
> –Ramesh Narayan, astrophysicist
> (active galactic nuclei, accretion disk flow)

> [I]n practice we don't really care whether an object is 'precisely' a black hole. It is enough to know that it acts approximately like a black hole for some finite amount of time.... [This is] something that we can observe and test.
>
> –Don Marolf, theoretical physicist
> (semi-classical gravity, string theory, holography)

> [A black hole is] a region which cannot communicate with the outside world for a long time (where 'long time' depends on what I am interested in).
>
> –Bill Unruh, theoretical physicist
> (classical general relativity, quantum field theory
> on curved spacetime, analogue gravity)

> Today 'black hole' means those objects we see in the sky, like for example Sagittarius A*.
>
> –Carlo Rovelli, theoretical physicist
> (classical general relativity, loop quantum gravity,
> cosmology, foundations of quantum mechanics)

thermodynamic behaviour. The presence of Hawking radiation, a consequence of the semi-classical approach, allows us to define a physical temperature for a black hole[24]. Semi-classical proofs of the generalized second law of thermodynamics justify the attribution of entropy to a black hole proportional to its area[25]. In the standard semi-classical picture, moreover, most researchers hold that the classical characterizations of black holes are unproblematic (or, at least, no more problematic than in the strictly classical context). The geometry is classical, they reason, so we can avail ourselves of all the tools we use to characterize black holes in the classical regime. Nonetheless, in so far as we do accept the semi-classical picture of black holes evaporating as they emit Hawking radiation, we must give up entirely on the idea of black holes as eternal, global objects, and use that idealization with care. The very presence of Hawking radiation itself, moreover, independently of the role it may play in black hole evaporation, means that we also may need to give up on the classical idea of black holes as perfect absorbers, and all the many important consequences that property entails.

> If we do accept the picture [of semi-classical gravity], then black holes become for the first time now, in this context, true physical systems—they have thermodynamic properties.
>
> – Daniele Oriti, theoretical physicist
> (semi-classical gravity, group field theory quantum gravity)

That, however, is a claim that is delicate to make precise, exactly because of the subtle interplay between the quantum effects of matter and the classical geometry. It is difficult to say with precision and clarity whether or not Hawking radiation shows that the interior of a black hole cannot be wholly isolated causally from its exterior. That ambiguity, however, calls into question the very distinction between the interior and the exterior of a black hole that the idea of an event horizon is supposed to explicate. I believe the idea of a black hole in the semi-classical context is not so clear cut as almost all physicists working in the field seem to think. Indeed, that black holes seem to have a non-trivial thermodynamics pushes us towards the view that there is an underlying dynamics of micro-degrees of freedom that is not and seemingly cannot be captured in the semi-classical picture, perhaps undermining the very framework that suggested it in the first place. In the same vein, it is well to keep in mind that none of the results in the semi-classical domain about black hole thermodynamics come from fundamental theory, but rather from a patchwork of different methods based on different intuitions and principles. As I mentioned already in the introduction, the semi-classical picture comes from trying to combine in completely novel ways two theories that are in manifest tension with each other, absent the guidance and constraint of experimental or observational knowledge. I think it behooves us to show far more caution in accepting the results of semi-classical black hole thermodynamics than is common in the field.

In other approaches with a semi-classical flavour, such as the conjectured duality between gravitational physics in anti-de Sitter spacetime and conformal field theories on its boundary (AdS-CFT)[26], and many projects based on holography more generally[27–29], it is difficult to define black holes at all in any direct way. In such approaches, one posits that the classical gravitational physics in an interior region of a spacetime is entirely captured by the physics of a quantum field on the boundary of the region (the time-like boundary at infinity in anti-de Sitter spacetime, for example). It is not easy to read off from the boundary physics whether anything resembling a black hole in any of its many guises (a horizon of a particular sort, for instance) resides in the interior.

There are attempts to do so, however, by isolating characteristic features of the configuration and evolution of the quantum fields on the boundary associated with black hole spacetimes in the interior. The holographic principle would then suggest that one identify those field configurations having maximal entropy as black holes. In a similar vein, some physicists working in holography and string theory, such as Juan Maldacena (personal communication), suggest that one characteristic feature of black holes is that their dynamical evolution is maximally chaotic, part and parcel of their purported entropy-maximization properties[30]. Others, such as 't Hooft (personal communication), reject that idea, contending that the main gravitational effect that governs how black holes behave is completely linear, and so they cannot serve as information scramblers in the sense championed by many others in the holography community. One physicist's characteristic property is another's mistaken claim.

Even if one does accept any of the glosses available in holography, one must face the fact that it is difficult to extract from the physics of the boundary field anything about the physics of the interior of a classical event horizon, a well known problem in these approaches. Any definition that cannot handle the interior of a black hole, however, must have a demerit marked against it. No known quantum effect, nor any other known or imagined physical process, can cause spacetime simply to stop evolving and vanish, as it were, once matter crosses its Schwarzschild radius. Perhaps nothing inside a horizon can communicate with the outside, but that does not mean it is not part of the world. As such, the mettle of physics demands that we try to understand it.

In quantum gravity in general, most agree that the problems of defining a black hole in a satisfactory manner become even more severe. There is, for instance, in most programmes of quantum gravity, nothing that corresponds to an entire classical history on which to base something like the traditional definition. Even trying to restrict oneself to quasi-local structures such as the apparent horizon has manifest problems: in the quantum context, in order to specify the geometry of such a surface, one in effect has to stipulate simultaneously values for the analogues of both the position and momentum of the relevant micro-structure, a task that quantum mechanics strongly suggests cannot be coherently performed.

Box 2 | Classical relativity and semi-classical gravity views on black holes

> I'd ... define a causal horizon as the boundary of the past of an infinite time-like curve [that is, the past of the worldline of a potential observer], and the black hole [for that observer] as the region outside the past.
>
> –Ted Jacobson, theoretical physicist
> (classical general relativity, semi-classical gravity, entropic gravity)

> We [mathematicians] view a black hole to be a natural singularity for the Einstein equation, a singularity shielded by a membrane [that is, a horizon].
>
> –Shing-Tung Yau, mathematician, mathematical physicist
> (classical relativity, Yang-Mills theory, string theory)

> A black hole is the solution of Einstein's field equations for gravity without matter, which you get after all matter that made up a heavy object such as one or more stars, implodes due to its own weight.
>
> –Gerard 't Hooft, theoretical physicist
> (standard model, renormalizability, holography)

> I have no idea why there should be any controversy of any kind about the definition of a black hole. There is a precise, clear definition in the context of asymptotically flat spacetimes, [an event horizon].... I don't see this as any different than what occurs everywhere else in physics, where one can give precise definitions for idealized cases but these are not achievable/measurable in the real world.
>
> –Bob Wald, theoretical physicist
> (classical general relativity, quantum field theory on curved spacetime)

> It is tempting but conceptually problematic to think of black holes as objects in space, things that can move and be pushed around. They are simply not quasi-localized lumps of any sort of 'matter' that occupies [spacetime] 'points'.
>
> –Domenico Giulini, theoretical physicist
> (classical general relativity, canonical quantum gravity, foundations of quantum mechanics)

> One can try to define a black hole in the context of holography and AdS-CFT as a macroscopic *N*-body solution to the quantum field theory that evolves like a fluid on the boundary of spacetime, which one can argue are the only solutions with horizons in the interior.
>
> –Paul Chesler, theoretical physicist
> (numerical relativity, holography)

> In analogue gravity things get more difficult, since the dispersion relation could mean that low energy waves cannot get out [of the horizon] while high energy ones can (or vice versa).
>
> –Bill Unruh, theoretical physicist
> (classical general relativity, quantum field theory on curved spacetime, analogue gravity)

> The versions of the description [of black holes] used tacitly or explicitly in different areas of classical physics (e.g. astrophysics and mathematical general relativity) differ in detail but are clearly referring to the same entities.
>
> –David Wallace, philosopher
> (foundations of quantum mechanics, statistical mechanics, cosmology)

> Ideally the definition used in quantum gravity reduces to the one in classical general relativity in the limit ħ goes to zero.... But since no one agrees on what a good theory of quantum gravity is (not even which principles it should satisfy), I don't think anyone agrees on what a black hole is in quantum gravity.
>
> – Beatrice Bonga, theoretical physicist
> (gravitational radiation, quantum gravity phenomenology)

One strategy for characterizing a black hole common to many approaches to quantum gravity is to ask, what particular kind of ensemble or assembly of building blocks constructed from the fundamental degrees of freedom 'looks like' a black hole, when one attempts to impose on them in some principled way a spatiotemporal or geometrical 'interpretation'? The idea is to try to put together 'parts' of the classical picture of a black hole one by one—find properties of an underlying quantum ensemble that make the resulting 'geometry' look spherically symmetric, say, and make it amenable to having a canonical area attributed to it, and so on, building up to the semi-classical picture[31]. It is difficult to test the conjecture that this will correspond to a classical black hole, however, in any known programme of quantum gravity, because it is difficult to reconstruct the causal structure of the 'resulting' classical geometry. A related strategy that suggests itself, inspired by the holographic principle, is to put together a quantum ensemble that in some sense is sharply peaked around a spherically symmetric geometry at the semi-classical level, a geometry moreover that respects the quasi-local conditions imposed by the classical picture of what a horizon should be. One then attempts to compute the entropy, maximizes it, and finally declares that the resulting ensemble is the definition of a black hole. The conjecture that this corresponds to a classical black hole is, again, difficult to verify theoretically, and of course impossible at the present time to test by experiment, and will be so for the foreseeable future.

Finally, although strictly speaking not work in gravitational physics, it is of interest to look briefly at so-called analogue models of gravity[32,33]. The explosion of work in that field centres on generalizations of the idea of a black hole, in the guise of a horizon of an appropriate sort appearing in a broad range of non-gravitational types of physical systems. The kinds of horizon at issue here will of necessity be generalizations in some sense of the kinds one finds in relativity, since one does not have available the full toolbox of classical spacetime geometry to work with. The fundamental problem is that the horizons one deals with in analogue systems are never true one-way barriers. This raises fascinating problems about how much or even whether at all one should trust the results of experimental and theoretical work in that field to translate into confirmatory support for the semi-classical gravity systems they are analogue models of refs [34,35]. Sadly, space does not permit discussing those problems here.

Why it matters

I believe there is a widespread hope across the many fields of physics in which black holes are studied that, though the conceptions, pictures, and definitions used differ in manifestly deep and broad ways, nonetheless they are all at bottom trying to get at the same thing. It is difficult otherwise to see how work in one area is to make fruitful contact with work in all the other areas. It is, however, at this point only a hope. Much work must be done to make clear exactly how all those different definitions, characterizations, and conceptions relate to each other, so we can have confidence when we attempt to apply results from one field to problems in another. That is why the question matters.

Box 3 | Quantum gravity views on black holes

I would not define a black hole [in this way]: by its classical central singularity. To me it is clear that that is an artefact of the limitations of general relativity, and including quantum effects makes it disappear.

–Francesca Vidotto, theoretical physicist
(loop quantum gravity, quantum gravity phenomenology)

A primary motivation of my research on quasi-local horizons was to find a way of describing black holes in a unified manner in the various circumstances they arise in fundamental classical physics, numerical relativity, relativistic astrophysics and quantum gravity.

–Abhay Ashtekar, theoretical physicist
(classical general relativity, loop quantum gravity, cosmology)

Black holes are not clearly defined in string theory and holography.

–Andy Strominger, theoretical physicist
(string theory, holography)

[T]he event horizon … is a *spacetime concept*, and spacetime itself is a classical concept. From canonical gravity we learn that the concept of spacetime corresponds to a particle trajectory in mechanics. That is, after quantization the spacetime disappears in quantum gravity as much as the particle trajectory disappears in quantum mechanics.

–Claus Kiefer, theoretical physicist
(semi-classical gravity, canonical quantum gravity)

Consider Hawking radiation. It is a problem oddly unremarked in the literature that, in the semi-classical picture, Hawking radiation is not blackbody radiation in the normal sense. Blackbody radiation, such as the electromagnetic radiation emitted by a glowing lump of hot iron, is generated by the dynamics of the micro-degrees of freedom of the system itself—in the case of iron, the wiggling and jiggling of the iron's own atoms and free electrons that makes them radiate. That is not the mechanism by which Hawking radiation is produced. In the semi-classical picture, Hawking radiation is not generated by the dynamics of any micro-degrees of freedom of the black hole itself, but rather by the behaviour of an external quantum field in the vicinity of the horizon. The hope, presumably, is that a satisfactory theory of quantum gravity will be able to bring these two *prima facie* disparate phenomena—the dynamics of the horizon on the one hand, and the dynamics of the external quantum field on the other—into explicit and harmonious relation with each other so as to demonstrate that the temperature of the thermalized quantum radiation is a sound proxy for the temperature of the black hole itself as determined by the dynamics of its very own micro-degrees of freedom. Since Hawking radiation is universally viewed as the strongest evidence in favour of attributing a temperature to black holes, and so attributing thermodynamic properties more generally to them, the lack of such an explicit connection ought to be troubling. It ought to become even more troubling when one considers the difficulties of defining black holes in all the different relevant contexts, and relating those different definitions in rigorous, clear, precise ways. How can the physicists across different fields hope to agree on an answer when they do not even agree on the question?

> You [Curiel] suggest that it should be troubling that black hole temperature seems very different from the temperature of ordinary matter. I find this very intriguing and exciting, not troubling.
>
> – Bob Wald, theoretical physicist
> (classical general relativity, quantum field theory on curved spacetime)

I suspect there will never be a single definition of ‘black hole’ that will serve all investigative purposes in all fields of physics. I think the best that can be done, rather, is, during the course of an investigation, to fix a list of important, characteristic properties of and phenomena associated with black holes required for one's purposes in the context of interest, and then to determine which of the known definitions imply the members of that list. If no known definition implies one's list, one either should try to construct a new definition that does (and is satisfactory in other ways), or else one should conclude that there is an internal inconsistency in one's list, which may already be of great interest to learn. Here are potentially characteristic properties and phenomena some subset of which one may require or want:

- possesses a horizon that satisfies the four laws of black hole mechanics;
- possesses a locally determinable horizon;
- possesses a horizon that is, in a suitable sense, vacuum;
- is vacuum with a suitable set of symmetries;
- defines a region of no escape, in some suitable sense, for some minimum period of time;
- defines a region of no escape for all time;
- is embedded in an asymptotically flat spacetime;
- is embedded in a topologically simple spacetime;
- encompasses a singularity;
- satisfies the no-hair theorem;
- is the result of evolution from initial data satisfying an appropriate Hadamard condition (stability of evolution);
- allows one to predict that final, stable states upon settling down to equilibrium after a perturbation correspond, in some relevant sense, to the classical stationary black hole solutions (Schwarzschild, Kerr, Reissner–Nordström, Kerr–Newman);
- agrees with the classical stationary black hole solutions when evaluated in those spacetimes;
- allows one to derive the existence of Hawking radiation from some set of independent principles of interest;
- allows one to calculate in an appropriate limit, from some set of independent principles of interest, an entropy that accords with the Bekenstein entropy (that is, is proportional to the area of a relevant horizon, with corrections of the order of $\hbar$);
- possesses an entropy that is, in some relevant sense, maximal;
- has a lower-bound on possible mass;
- is relativistically compact.

This list is not meant to be exhaustive. There are many other such properties and phenomena one might need for one's purposes. It is already clear from this partial list, however, that no single definition can accommodate all of them. It is also clear from the discussion that, even within the same communities, different workers will choose different subsets of these properties for different purposes in their thinking about black holes.

One may conclude that there simply is no common conceptual core to the pre-theoretical idea of a black hole, that the hopeful conjecture that physicists in different fields all refer to the same entity with their different definitions has been thrown down on the floor and danced upon. I would not want to draw that conclusion, though neither do I want to wholly endorse the strong claim that there is a single entity behind all those multifarious conceptions. I would rather say that there is a rough, nebulous concept of a black hole shared across physics, that one can explicate that idea by articulating a more or less precise definition that captures in a clear way many important features of the nebulous idea, and that this can be done in many different ways, each appropriate for different theoretical, observational, and foundational contexts. I do not see this as a problem, but rather as a virtue. It is the very richness and fruitfulness of the idea of a black hole that leads to this multiplicity of different definitions, each of use in its own domain. I doubt the idea would be so fruitful across so many fields if they all were forced to use a single, canonical definition.

Received: 4 August 2018; Accepted: 18 September 2018;

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Acknowledgements

I am grateful to all the many physicists and philosophers who responded to my questions with thoughtful enthusiasm—you are too many to name, but you know who you are. This Perspective would have been much poorer without the illumination of your discussions. I must, however, single out A. Ashtekar, B. Bonga, P. Chesler, B. Geroch, D. Giulini, G. 't Hooft, T. Jacobson, C. Kiefer, A. Loeb, J. Maldacena, D. Marolf, R. Narayan, D. Oriti, C. Rovelli, K. Thébault, B. Unruh, B. Wald, D. Wallace, and S.-T. Yau for supererogatory input and further discussion. I thank B. Unruh and B. Wald also for their recollections of the attitude of relativists in the 1960s and 1970s to black holes, as well as A. Loeb and R. Narayan for discussion about the reception of the idea in the community of astrophysicists at the same time. Some of this work was completed at the Black Hole Initiative at Harvard University, which is funded through a grant from the John Templeton Foundation. The rest was completed at the Munich Center for Mathematical Philosophy, in part funded by a grant from the Deutsche Forschungsgemeinschaft (grant number CU 338/1-1 AOBJ 628412).

Competing interests

The author declares no competing interests.

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