# Defining black holes

Mathematical concepts are by nature well defined. A Borel measure on a topological space is a measure defined over all open sets. A Banach space is a vector space equipped with a norm and complete in the sense that a Cauchy sequence of vectors always converges to a well-defined limit within the space. All is set out in precise definition. There's no quibbling.

Physics concepts aren't like that. To one physicist, an electron is a tiny particle carrying mass, charge and spin, detectable in a metallic sample in the lab. To another, it is a possible excitation of an abstract quantum field. Or consider entropy. In thermodynamics, it's an objective, measurable property of a physical system, linked to the number of distinct microscopic configurations corresponding to a macroscopic state. Yet the notion also has a mathematical definition based on information, and often takes on a more subjective quality, linked to an observer's ignorance. Mathematical physicist John von Neumann once remarked that anyone mentioning entropy in an argument has an inherent advantage, "because no one really understands what entropy is."

Perhaps an even better example is the notion of a black hole, something that one might expect physicists to describe in fairly uniform terms. But physicist Erik Curiel recently asked a diverse set of researchers, "what is a black hole?" — and received a surprisingly broad set of answers. As he writes in a preprint (https://arxiv.org/abs/1808.01507) examining the results, most physicists "know what a black hole is, right up until the moment you blindside them with the request for a definition." The responses suggest that there is no one useful concept of a black hole, but many overlapping and often inconsistent interpretations. There's nothing bad in this — it may be a crucial aspect of the exploratory power of science.

Curiel expected most frequently to hear the classic definition of the event horizon, now found in the standard texts on general relativity. This result grew from efforts in the 1960s to understand the spacetime consequences of the gravitational collapse of massive bodies, especially stars, and formalized the intuition that a black hole is a 'region of no escape'. An event horizon for some spacetime divides it cleanly into two disjoint regions. Inside the horizon, all points must asymptotically fall into the black hole, and trajectories starting here can never escape to the zone outside the horizon. Any spacetime with an event horizon must contain a black hole.

This is the idea most often invoked in popular discussions of black holes, and yet the physicists who mentioned this definition to Curiel typically did so to point out its shortcomings. Most prominently, actually locating a classical event horizon requires global knowledge of the entire spacetime, through all of infinite space and for all time. No local measurements can ever determine the location of an event horizon. There's just no way to carry out the task.

Hence, this definition may not be so useful. Or, as one respondent put it, the existence of a classical event horizon "just doesn't seem to be a verifiable hypothesis."

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As a result, some physicists have looked for more local ways to define a black hole. One idea is to define a so-called apparent horizon, a structure that should always exist if a classical event horizon exists, but the location of which can be determined from local information alone. An apparent horizon is a closed two-dimensional surface with the property that light rays emanating outward from any point on the surface are tangential to the surface — and hence cannot escape it. In principle, this can be determined by measurements local to this surface alone, not infinitely far away.

There's been lots of research on this and related ideas over the past two decades, and yet there's also another problem. As Curiel notes, the apparent horizon doesn't divide the interior and exterior of a black hole as cleanly as the true event horizon does. It's not certain that something moving into the interior of such a horizon will not escape later. Moreover, defining such a horizon requires choosing a particular frame of reference, and so it is not a relativistically invariant object.

But many practically minded physicists don't worry too much about such issues. Most astrophysicists have accepted since the early 2000s that black holes are real astrophysical objects, and that a supermassive black hole almost certainly lies within the intense radio source Sgr A, at the centre of the Milky Way. A black hole to many astrophysicists now just means any sufficiently compact and massive system that collapse cannot end in a neutron star. As one put it in their response to Curiel, "A black hole is a compact body of mass greater than 4 Solar masses—the physicists have shown us there is nothing else it can be."

But this doesn't quite work either. As Curiel notes, this simple empirical recipe isn't enough to distinguish a black hole from a naked singularity, a more exotic possibility allowed by general relativity, in which an event horizon does not exist. There may turn out to be ways to exclude the possibility of naked singularities on other grounds, he observes, or to find observational ways to distinguish the two things. But this isn't the case yet.

There are even further complications in thinking about just what a black hole really is. The image almost all physicists have in mind, whether inspired by mathematics or observations, is of a highly compact and extremely massive object formed through gravitational collapse. But black holes with event horizons can arise in other ways too. Curiel points to the work of physicist Robert Geroch, who showed years ago that if all the stars in a galaxy such as the Milky Way were displaced towards the Galactic Centre, while maintaining their proportionate distances from each other, they would all fall within their joint event horizon long before they collide. An event horizon with an interior cut off from the rest of the Universe can form without any collapse at all.

So there turn out to be many working definitions of a black hole, useful to physicists studying and thinking about gravitational astrophysics. Curiel mentions some further definitions linked to work in areas such as quantum gravity. It's not reflective of any sloppiness in the field, but the rich nuance of the concept. The phase space of physicists' conceptual repertoire is occupied by a broad population of black hole definitions, rather than one precise point. That's probably good, as a single agreed upon definition might well be stifling. ❐

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