graphic principle not just to black holes but also to the universe at large, providing a recipe for how to create space—or at least some of it. For instance, a two-dimensional space could be threaded by fields that, when structured in the right way, generate an additional dimension of space. The original two-dimensional space would serve as the boundary of a more expansive realm, known as the bulk space. And entanglement is what knits the bulk space into a contiguous whole.

In 2009 Mark Van Raamsdonk of the University of British Columbia gave an elegant argument for this process. Suppose the fields at the boundary are not entangled—they form a pair of uncorrelated systems. They correspond to two separate universes, with no way to travel between them. When the systems become entangled, it is as if a tunnel, or wormhole, opens up between those universes, and a spaceship can go from one to the other. As the degree of entanglement increases, the wormhole shrinks in length, drawing the universes together until you would not even speak of them as two universes anymore. "The emergence of a big spacetime is directly tied into the entangling of these field theory degrees of freedom," Van Raamsdonk says. When we observe correlations in the electromagnetic and other fields, they are a residue of the entanglement that binds space together.

Many other features of space, besides its contiguity, may also reflect entanglement. Van Raamsdonk and Brian Swingle, now at the University of Maryland, College Park, argue that the ubiquity of entanglement explains the universality of gravity—that it affects all objects and cannot be screened out. As for black holes, Leonard Susskind of Stanford University and Juan Maldacena of the Institute for Advanced Study in Princeton, N.J., suggest that entanglement between a black hole and the radiation it has emitted creates a wormhole—a back-door entrance into the hole. That may help preserve information and ensure that black hole physics is reversible.

Whereas these string theory ideas work only for specific geometries and reconstruct only a single dimension of space, some researchers have sought to explain how all of space can emerge from scratch. For instance, ChunJun Cao, Spyridon Michalakis and Sean M. Carroll, all at the California Institute of Technology, begin with a minimalist quantum description of a system, formulated with no direct reference to spacetime or even to matter. If it has the right pattern of correlations, the system can be cleaved into component parts that can be identified as different regions of spacetime. In this model, the degree of entanglement defines a notion of spatial distance.

In physics and, more generally, in the natural sciences, space and time are the foundation of all theories. Yet we never see spacetime directly. Rather we infer its existence from our everyday experience. We assume that the most economical account of the phenomena we see is some mechanism that operates within spacetime. But the bottom-line lesson of quantum gravity is that not all phenomena neatly fit within spacetime. Physicists will need to find some new foundational structure, and when they do, they will have completed the revolution that began just more than a century ago with Einstein.

George Musser is a contributing editor for *Scientific American.* He is author of *Spooky Action at a Distance* (2015) and *The Complete Idiot's Guide to String Theory* (2008).

What Is Dark Matter?

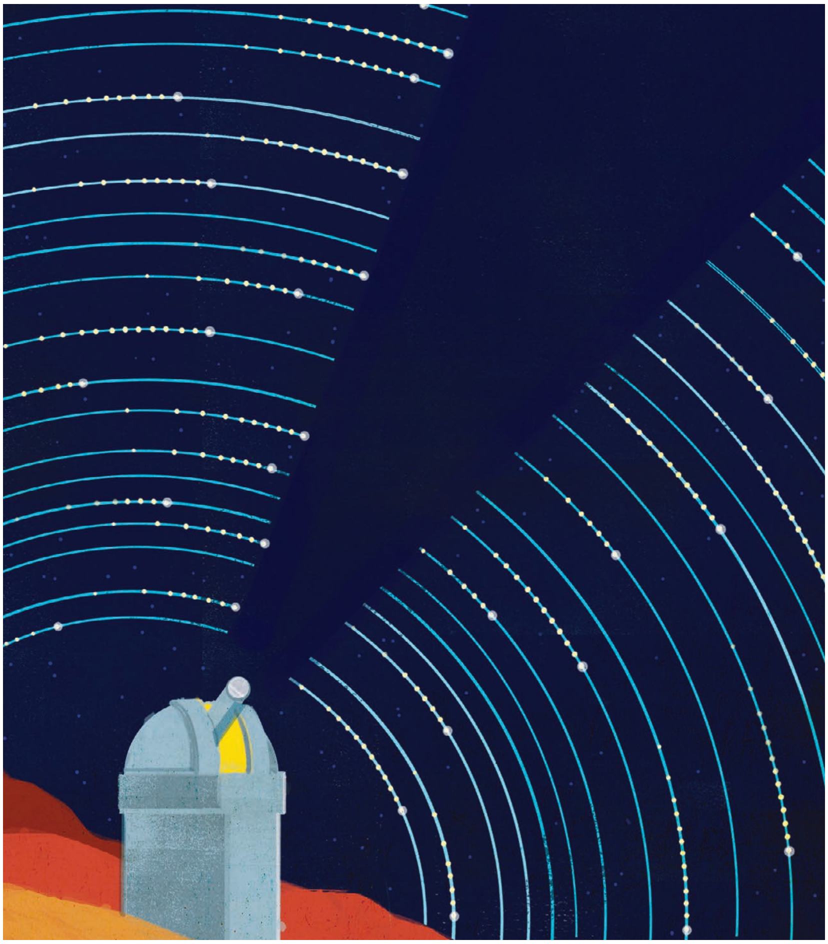
An elusive substance that permeates the universe exerts many detectable gravitational influences yet eludes direct detection

By Lisa Randall

Physicists and astronomers have determined that most of the material in the universe is "dark matter"—whose existence we infer from its gravitational effects but not through electromagnetic influences such as we find with ordinary, familiar matter. One of the simplest concepts in physics, dark matter can nonetheless be mystifying because of our human perspective. Each of us has five senses, all of which originate in electromagnetic interactions. Vision, for example, is based on our sensitivity to light: electromagnetic waves that lie within a specific range of frequencies. We can see the matter with which we are familiar because the atoms that make it up emit or absorb light. The electric charges carried by the electrons and protons in atoms are the reason we can see.

Matter is not necessarily composed of atoms, however. Most of it can be made of something entirely distinct. Matter is any material that interacts with gravity as normal matter does—becoming clumped into galaxies and galaxy clusters, for example.

There is no reason that matter must always consist of charged particles. But matter that has no electromagnetic interactions will be invisible to our eyes. So-called dark matter carries no (or as yet undetectably little) electromagnetic charge. No one has seen it directly with his or her eyes or even with sensitive optical instruments. Yet we believe it is out there because of its manifold gravitational influences. These include dark matter's impact on the stars in our galaxy (which revolve at speeds too great for ordinary matter's gravitational force to rein in) and the motions of galaxies in galaxy clusters (again, too fast to be accounted for only by matter that we see); its imprint on the cosmic microwave background radiation left over from the time of the big bang; its influence on the trajec-



tories of visible matter from supernova expansions; the bending of light known as gravitational lensing; and the observation that the visible and invisible matter gets separated in merged galaxy clusters.

Perhaps the most significant sign of the existence of dark matter, however, is our very existence. Despite its invisibility, dark matter has been critical to the evolution of our universe and to the emergence of stars, planets and even life. That is because dark matter carries five times the mass of ordinary matter and, furthermore, does not directly interact with light. Both these properties were critical to the creation of structures such as galaxies—within the (relatively short) time span we know to be a typical galaxy lifetime—and, in particular, to the formation of a galaxy the size of the Milky Way. Without dark matter, radiation would have prevented clumping of the galactic structure for too long, in essence wiping it out and keeping the universe smooth and homogeneous. The galaxy essential to our solar system and our life was formed in the time since the big bang only because of the existence of dark matter.

Some people, on first hearing about dark matter, feel dismayed. How can something we do not see exist? At least since the Copernican revolution, humans should be prepared to admit their noncentrality to the makeup of the universe. Yet each time people learn about it in a new context, many get confused or surprised. There is no reason that the matter we see should be the only type of matter there is. The existence of dark matter might be expected and is compatible with everything we know.

Perhaps some confusion lies in the name. Dark matter should really be called transparent matter because, as with all transparent things, light just passes through it. Nevertheless, its nature is far from transparent. Physicists and astronomers would like to understand, at a more fundamental level, what exactly dark matter is. Is it made up of a new type of fundamental particle, or does it consist of some invisible, compact object, such as a black hole? If it is a particle, does it have any (albeit very weak) interaction with familiar matter, aside from gravity? Does that particle have any interactions with itself that would be invisible to our senses? Is there more than one type of such a particle? Do any of these particles have interactions of any sort?

My theoretical colleagues and I have thought about a number of interesting possibilities. Ultimately, however, we will learn about the true nature of dark matter only with the help of further observations to guide us. Those observations might consist of more detailed measurements of dark matter's gravitational influence. Or—if we are very lucky and dark matter does have some tiny, nongravitational interaction with ordinary matter we have so far failed to observe—big underground detectors, satellites in space or the Large Hadron Collider at CERN near Geneva might in the future detect dark matter particles. Even without such interactions with ordinary matter, dark matter's self-interactions might have observable consequences. For example, the internal structure of galaxies at small scales will be different if dark matter's interactions with itself rearrange matter at galactic centers. Compact or other structures akin to the Milky Way, such as the bright gas clouds and stars we see when we look at the night sky, could indicate one or more distinct species of dark matter particles that interact with one another. Or hypothesized particles called axions that interact with magnetic fields might be detected in laboratories or in space.

For a theorist, an observer or an experimentalist, dark matter is a promising target for research. We know it exists, but we do not yet know what it is at a fundamental level. The reason we do not know might be obvious by now: it is just not interacting enough to tell us, at least so far. As humans, we can only do so much if ordinary matter is essentially oblivious to anything but dark matter's very existence. But if dark matter has some more interesting properties, researchers are poised to find them—and, in the process, to help us more completely address this wonderful mystery.

Lisa Randall is Frank B. Baird, Jr., Professor of Science at Harvard University. She serves on *Scientific American*'s board of advisers. Among her many books is *Dark Matter and the Dinosaurs: The Astounding Interconnectedness of the Universe* (2015).