

'Pulsing with wisdom and
humanity... a masterpiece'

Ed Yong

How Infrastructure Works

Transforming
our shared
systems for a
changing world

Deb Chachra

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*Dedicated to all those individuals—
past, present, and future—
whose ongoing labor, care, and attention
make our essential infrastructural systems possible.*

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Central to any new order that can shape and direct technology and human destiny will be a renewed emphasis on the concept of justice.

URSULA M. FRANKLIN, *The Real World of Technology*

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One

BEHIND THE LIGHTS

On a rainy Mother's Day in 2002, along with two hundred thousand other people, I went for a walk on a brand-new bridge.

The Leonard P. Zakim Bunker Hill Memorial Bridge in Boston is brilliant white, all soaring towers and parallel lines, echoing a nearby obelisk and evoking a ship under full sail. It's one of the world's widest cable-stayed bridges, and its roadbed carries ten lanes of Interstate 93 traffic over the Charles River before diving under the peninsula of the downtown core. A few weeks before it was opened to cars, local residents were invited to cross it on foot. And we came, five times as many visitors as were expected, despite the weather. My friend and I waited for hours, huddled under our umbrellas, before we finally made it onto the bridge. We craned our necks to drink it all in, knowing it was almost certainly the one and only time we would get to traverse it at our own speed and under our own power.

In retrospect, the organizers probably shouldn't have been quite so surprised at the demand. In 1987, when the Golden Gate Bridge was fully opened to pedestrians to celebrate its fiftieth anniversary, nearly three hundred thousand people were on the deck—more weight than bumper-to-bumper traffic—and the organizers had to turn away another half a million.

Conservation biologists sometimes refer to animals like pandas, elephants, and polar bears as “charismatic megafauna.” Large, easily recognizable, and beloved, they make excellent spokescreatures for wildlife and for their homes. All over the world, charismatic megastructures are the public faces of our collective infrastructural systems. Bridges, of course, but also the soaring spaces of railway stations, from Grand Central Terminal in New York City to the Chhatrapati Shivaji Maharaj Terminus in Mumbai. In my hometown of Toronto, the CN Tower, built to be a communications hub, makes the skyline instantly recognizable. The Hoover Dam, in the desert outside Las Vegas, hosts seven million visitors every year. We *love* our charismatic megastructures. Their size and complexity might inspire awe, but I think it also has to do with the way that we feel like they belong to all of us, not individually but together, in much the same way as cathedrals and other sacred spaces. Not for nothing did Joan Didion describe driving on Los Angeles highways as a “secular communion.”

Years after I dragged my friend out in the rain with me to walk on the Zakim Bridge, my nephews came to visit and we took an amphibious boat tour of the city. The guide told us about that one, now-legendary day in May when the bridge was open to pedestrians. I remember, I told them. I was there. My family was unsurprised, because they know I’ve been fascinated by science and engineering my entire life. The first thing I ever remember wanting to be as a kid was an astronaut—it was the 1970s, the cultural peak of space exploration. By the time I was ten, I wanted to be a nuclear physicist, and this took me all the way through to a degree in engineering physics. Like many women of my generation who went into the field, I had a role model close by, my father. He’d grown up and earned a degree in electrical engineering in a newly independent India before deciding he wanted to see more of the world. In the late 1960s, Canada, like the U.S., was opening its doors to non-European immigrants. My father enrolled in an MBA program at the University of Alberta and when he graduated, he took a job with Ontario Hydro, the public electrical utility for the province. His young family

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moved to the outskirts of Toronto and he started work at the place where he would eventually spend his entire professional career. A few months later, I was born. And a few months after that, in the next town over, one of the first large-scale nuclear power stations in Canada came online. I grew up on a street that ran down to a sandy beach on Lake Ontario, and when we picnicked and played in the water, the plant was easily visible, eight imposing gray concrete domes and a single massive cylindrical structure on the shoreline. Behind the facility, rows of electrical transmission towers marched along a wide, green right-of-way, first through the nearby suburban housing and then all over the city and region. Best of all, for my tech-obsessed childhood self, they had a visitor center with a nuclear power-themed interactive science museum. In my memory, it's all buttons and flashing lights, with cutaway models explaining the different systems and a walk-through mock-up of the reactor core. The Pickering Nuclear Generating Station was my local, personal charismatic megastructure. When I had to give a five-minute speech to my sixth-grade class at school, my topic was obvious: my fellow students got a lecture about the CANDU (CANadian Deuterium Uranium) reactors at our local power station, illustrated with a set of overhead transparencies my dad had brought home from work.

Scientists and engineers have a concept of *elegance*, which is among the highest praise that can be given to a theory, a proof, or a device. It's hard to explain exactly what it is, but it incorporates ideas of efficiency or parsimony—accomplishing something with a minimum of effort, energy, or materials. Elegance in engineering often encompasses the surprising and very particular use of the specific resources that are available. Beauty might be part of it, but mostly as something inherent in the design, and the skill and care of its manufacture is part of it too. For example, the graceful curves of suspension bridges, like the Brooklyn Bridge or the Golden Gate, derive from the way that cables are shaped by gravity as they bear the weight of the roadbed below. My local power station probably wouldn't be described as beautiful, but what was going on inside possessed undeniable engineering elegance. The

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reactor systems are carefully designed to produce and control the nuclear reactions that create heat, turning water into the pressurized steam which spins turbines and generates electricity. The CANDU design uses deuterium, an isotope of hydrogen, in the form of naturally occurring heavy water that's been purified out from ordinary water. It plays a safety-conscious dual role: the heavy water bathes the reactor core, supporting the nuclear reactions and also serving as a coolant. Because the reactor needs the deuterium to remain critical, a leak means that the core will fizzle out instead of overheating. What's more, the deuterium is so effective at sustaining nuclear fission that the uranium fuel only needs to be lightly enriched. That makes it easier and less dangerous to produce than other reactor fuels, and it's also much less amenable to being repurposed to make nuclear weapons.

Of course, as a kid I didn't think about any of the larger issues like limiting the risk of nuclear isotopes falling into the wrong hands or ways to deal with the long-term storage of radioactive waste. But even then, years before I took my first physics or engineering course, I could recognize the elegance and utility of the reactor design and how it made the most of what was available, whether that was locally mined uranium in the reactor core or frigid water from the depths of Lake Ontario for cooling. Today, I recognize this same elegance all over the world and across infrastructural systems, in a giant battery in Wales that's constructed from two lakes and the mountain between them and in the modular design of a solar plant outside Hyderabad, India. That elegance is a hallmark of infrastructure because these systems are almost always designed around the effective use of resources—above all, the use of energy. For most of human history, access to energy has enabled or limited what's possible. Harnessing and delivering energy, efficiently and at scale, has long been one of the main drivers for why and how societies have built out collective infrastructural systems.

The Zakim Bridge became an iconic part of the Boston skyline as soon as it was constructed. There are practical reasons for it to be such a dramatic structure—instead of being built on piers, it's a cable-stayed design, which

limits its impact on the Charles River below—but surely it was also so that a monumental effort to make something *less* visible would be recognized and valued. The bridge was built as part of the Central Artery/Tunnel Project, better known as the Big Dig, the decades-long, multibillion-dollar project in which the elevated expressway that carried Interstate 93 across downtown Boston was torn down and the highway was buried underground. Elephants, whales, and other charismatic megafauna help us to see and appreciate entire ecosystems, including all of the unregarded but critically important species, like tiny insects and nondescript flora. Charismatic megastructures can similarly help us see and appreciate whole infrastructural systems, even the parts that are buried or hidden. And while I might have started with my massive local nuclear power plant, I began to realize that I could see and learn from the tiniest parts of these networks too.

Seeing Beneath the Surface

The Old State House in downtown Boston was built in 1713, making it one of the oldest public buildings in the city. I must have walked past it dozens of times before my eye was caught by the bronze glint of a benchmark sunk into the granite steps of a side door. It's a medallion, a few inches in diameter, with markings that indicate that it was placed by the U.S. Coast and Geodetic Survey to serve as a reference point for mapping. I had to kneel and look carefully at its worn face in order to make out the date: 1936. Similar survey markers can be found all over the world—I once startled a friend by spotting a tiny red marker, labeled CADASTRE, as I was stepping off a curb in Lausanne, Switzerland (it would have been used to create a cadastral map, an administrative record of all the real estate in the country). A few years ago, I went to the southern end of Central Park to find a small, anonymous steel rod sunk into a granite boulder. It was a Randel bolt, one of the markers that were used to lay out the original grid pattern of Manhattan streets at the start of the nineteenth century. On the modern suburban

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campus where I teach engineering, there's a small, bright blue metal pin embedded into a pathway to mark where a nineteenth-century aqueduct passes under the athletic fields. In urban centers, cryptic symbols spray-painted onto the pavement tell utility workers where to dig and what they'll find when they do, in much the same way doctors use surgical markers to make notations on patients before making the first incision in an operation. Boston is one of a number of cities that uses repair tags, plastic disks that are labeled with the name of the utility company and a reference number. They're embedded into asphalt repair patch after work is complete in order to let the next work crew know that something has changed. On unpaved ground, I've spotted flags or feathery bundles of colored plastic fiber used to mark where gas and water lines lie below the dirt. The bright colors aren't just for visibility. They're a code: in most of the U.S., blue is used for potable water, green for sewage and runoff, red for electricity, orange for communications, and yellow for natural gas, with hot pink used for temporary markings.

At any given moment, there is almost certainly some element of some infrastructural system in my field of view. Indoors, I can look around to see electrical lights and outlets, and usually there's a heating vent, and maybe a faucet or a drain. A few tiny curved lines in the corner of my laptop screen or straight lines on my phone tell me I'm on a global telecommunications network. Outdoors, there's almost certainly a nearby road, or at least a footpath that connects to one. But seeing isn't perceiving—just because something is in our field of view doesn't mean that we consciously register it, much less understand what we're looking at. Humans are disturbingly good at filtering out anything in our vision that we're either accustomed to seeing or which doesn't appear meaningful. Charismatic megastructures notwithstanding, many of the visible parts of infrastructural systems fall into this perceptual chasm. Between their familiarity and their unannounced, unexplained presence, infrastructural systems are easy to see but just as easy to ignore, unless we bring our conscious attention to bear on them.

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Once we do, we begin to see that we are surrounded by networks, made visible not just by colorful squiggles but by sewer grates, telephone poles, mailboxes, access covers, transformer boxes, fire hydrants, railway lines, and on and on and on. The contrail of a jet airplane makes the invisible air travel corridors in the sky above us temporarily visible, just as spray paint does for underground ducts. Survey markers and street signs remind us that all of these networks were made possible by the centuries-long project of measuring the world, first with maps, then with clocks, and now with modern satellite mapping, which entangles the two. Even if the networks themselves are buried or intangible, we can visualize them by connecting the traces that we can see, knitting together people, buildings, and the world around us, in our home neighborhood or across the planet.

These visible markers show us not only the extent of these networks in space but also how they extend through *time*. Every marker, whether it's an imposing monument or a scrap of fabric, is there to send a message from the past to the future. Infrastructural networks are enduring, and that endurance shapes the way that new systems build on top of—or underneath, or alongside—the older ones. Water mains and gas pipes run along and beneath roads. Train tracks often followed watercourses as a path of least resistance through the terrain, telegraph lines were sent alongside the rails, and then roads were built along the same path, and electrical wires strung, and telephone cables. Because these networks are so important to the ways we do things, they have unparalleled continuity. We almost never rip them out and start over from scratch. Instead, infrastructural systems are repaired or rebuilt in modular increments, like steadily working through the replacement of water mains in a neighborhood or fixing potholes every spring. But that continuity has a flip side: it locks us into these ways of doing things. The QWERTY keyboard layout was designed to keep fast typists from jamming the keys on manual typewriters, but it's still in use on smartphone touchscreens. Decisions made decades or even centuries ago—how we treat wastewater, the use of alternating current instead of direct current for electricity

grids, pipelines laid for fossil fuels—all of these shape not just the technologies and systems in use today but those that haven't yet been built. That continuity means there's a path dependence—that the kinds of systems we have today depend on the characteristics of the systems that came before—in addition to growth and accumulation, as these systems build on each other. We now live surrounded by technological systems of nearly unimaginable scale, extent, and complexity.

Landscapes and Cloudscapes

My family's immigration story is intertwined with the rise of global civil aviation, and so my childhood was one of transcontinental flights to India to visit extended family. Even after a lifetime of flying, it's still a thrill for me to get on a plane, to feel the press of acceleration during takeoff and the lift as the wheels release their contact with the ground, and to gaze out of the window for hours, at the sky or the landscape or the ocean below. Air travel has never become mundane to me, not least because once I think about what's happening, it's a *lot*. First of all, there's the sheer improbability of being in a vehicle that weighs hundreds of tons and is somehow still miles above the ground, airborne only by virtue of its tremendous forward speed. Along with this is understanding that it's because of the expertise of the pilots and the continued functioning of the massive jet engines, along with the systems that connect them to the control surfaces of the plane, to say nothing of the ones that keep the cabin comfortable in the face of the killing cold and the suffocating absence of air just on the other side of the porthole, a few inches from my face.

Those are just the most obvious, visible parts. When we're over the middle of the Atlantic, quietly seated, or asleep or watching a movie, we're all comfortable and the engines continue to roar quietly because of everything that happened before we boarded: the inspection, maintenance, and repair of the plane, and its provisioning with supplies, from aviation kerosene to toilet paper. And behind that, all of the standards, regulations, and certifications,

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everything from the fire resistance of seat fabric to the rules around how many hours the flight crew can work, from how and when to file a flight plan to the pictographs in the toilet. Then beyond *that*, an entire international system of atomic clocks and satellites so that all the planes in flight can agree on exactly what time it is and where they are, as well as the global network of weather sensors and prediction. Very few of these technologies and systems even existed a century ago, and now they're far too complex for a single mind to grasp.

Carl Sagan famously said, "If you wish to make an apple pie from scratch, first you must invent the universe." Ever since I was a kid, whenever I find myself someplace far from city lights on a clear night, I take some time and stare up at the stars. It reminds me that we're all whirling through space, and that everything I can see in the sky will continue to move along its own path regardless of anything that happens on our planet. Sometimes it can feel like cosmic vertigo, but I mostly find the vastness and indifference of the universe strangely reassuring. Because if you wish to drink a Bloody Mary and watch a movie as you fly somewhere for a vacation, first you must invent an unutterably and increasingly complex international system that's not just technological but social and political and regulatory, in order to make an intercontinental flight safe and even mundane. When I think too hard about air travel, I can give myself the same vertiginous feeling I get when I stare up into a starry sky, but I find being enfolded in these global systems similarly reassuring. It's helped by the ordinary human reassurance that comes from observing or interacting with professionals working with competence and care. It's part of why I like it when planes have an in-flight channel for the radio chatter from the cockpit.

But here's the kicker—or rather, two kickers. One is that, unlike the stars, the systems that enable my transatlantic flights are *human* systems, created and sustained by and for humans. They were designed and built to get at a certain set of outcomes—safe air travel, for sure, but also profits for airlines, or to bolster national pride, or to provide mobility options for residents of that country, or other reasons. The other kicker is that even if you're

firmly on the ground, if you're reading these words, you are almost certainly still enmeshed in modern globe-spanning technological systems that have at least as much scale and complexity as civil aviation. The last half century or so has seen the rise of planetary networks not just for the movement of people but also of goods, in the form of supply chains enabled by the standardized shipping container, and of information, enabled by modern telecommunications. The growth in scale and extent of these systems have been in parallel with a steady increase in technological complexity, present not only in the obvious examples like computers but also in seemingly simple artifacts, like flimsy disposable plastic shopping bags. Whether it's a telephone or a T-shirt, most modern goods are made possible by cooperation and standards, the products of humans working together to make use of technologies that no one person can understand in their entirety. Every light switch connects to a system that's just as complicated as civil aviation and just as much a human creation full of human actors, as dependent on schedules, maps, standards, and regulations. The electrical grid, municipal water supplies, waste treatment facilities, motorized transport, food production systems, fossil fuel distribution, telecommunications—these technologies and networks underpin every aspect of the lives of a large fraction of the humans on the planet, whether directly or indirectly.

The Systems of the World

I've referred to a number of different systems, individually and collectively, as infrastructure. We can certainly intuit that they have something in common, so that it makes sense to group them together, but it's hard to articulate exactly what that is. What makes infrastructure, infrastructure?

“All of the stuff that you don't think about” turns out to be a surprisingly good starting point. For something to be considered infrastructure, its presence and characteristics are taken as a given. My bedside lamp needs

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electricity to function, and it plugs into an outlet, but I don't have to think much about the specific characteristics of the electricity: the voltage, the current, the frequency. The washing machine I use for my clothes needs not only electricity but also a supply of clean water. Some of that water comes from a hot-water heater, which itself relies on a piped-in supply of natural gas, and the dirty water drains into a sewage line. Four different infrastructural systems converge when I do my laundry. My ability to take these infrastructural systems for granted implies that there are underlying social agreements about what systems will be present and how they will function. They're not the only systems like this in our lives. A monetary system is a social agreement that money has value and can be traded for useful goods and services. A well-functioning legal system is a collective system that, among other characteristics, allows strangers to enter into contracts with confidence because all parties know that there are consequences for breaking them.

What electricity, water and sewage, telecommunications, and transportation—these familiar infrastructural systems—also have in common with each other is that they're technological systems. They're rooted in physical phenomena—the characteristics and behavior of matter and energy—and so require some kind of engineering to harness those phenomena. It might be as simple as digging a ditch to channel water flowing downhill into a slightly different direction, or it might be as complex as all the multitudinous technologies, from metallurgy to meteorology, that go into building a commercial jet plane and keeping it safely in the air. As an engineering professor, especially given my background in materials science, I have a deep awareness of how technologies are embedded in the physical world and how this makes infrastructure different from legal or monetary systems. Buying a cup of coffee might incorporate all sorts of technologies, from papermaking to RFID readers, but money itself doesn't require technology, much less any specific technology, to work. All it requires is that social agreement.

While infrastructural systems do involve social agreements around

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technologies, they share another important element. It's not just that everyone does things the same way. It's that there's a reason to do things the same way, together.

Most of the technological systems that we consider to be infrastructure are networks, connections between different places in the world. This is most obvious for transportation, ways to get from point A to point B: roads, rail networks, air travel, shipping, or transmodal combinations. Faucets and drains are points on our water and sewage systems that are connected by water mains, sewage pipes, reservoirs, and treatment plants; the oven in my kitchen is a node on the municipal network of natural gas pipes, as is the furnace of the building where I live. We're also embedded in electrical networks that light up and power our homes and workplaces, and telecommunications networks that connect us to others, once by dots and dashes, then by analog signals, and now increasingly by digital data, in all its varied permutations.

What makes networks special is not just that they're collective but that they can also be synergistic: the more people who use them, the more valuable they become for everyone. The larger the population of a settlement, for example, the more incentive there is to make the substantive upfront investment in building out a shared water supply. Every community, home, or business that is connected to a road or a telephone network makes the whole network more valuable for everyone else on it. The more people in your neighborhood who use electricity, the cheaper it becomes to deliver it. What's more, infrastructural systems often have benefits that go beyond the individual. Access to clean water reduces the risk of contagious waterborne disease for everyone, and electric lighting reduces the risk of fires. This intersection—technology, networks, and the value of universal access—is the key to why infrastructure is often considered a public good, in both the economic and everyday sense. And it's not static: the development and adoption of new networked technologies leads to new ideas of what's considered to be a universal need. We've been seeing this evolution happen in real time

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over the past decade or so as home broadband Internet access went from being useful but nonessential to being a primary means of interacting with systems and public services, including education.

As a child, I was most impressed by the technological elegance of infrastructure, and I still think that these systems are fascinating. As an adult, though, I've begun to see the networked, technological systems that are the focus of this book in a much different way. We might interact with them as individuals but they're inherently collective, social, and spatial. Because they bring resources to where they're used, they create enduring relationships not just between the people who share the network but also between those people and *place*, where they are in the world and the landscape the network traverses. These systems make manifest our ability to cooperate to meet universal needs and care for each other. We need those skills and behaviors, maybe more than ever before in human history. But that cooperation and care is by no means the whole story, because these systems also fail many people and even cause harm. Our infrastructural systems tell a story of who we are as a society or even a civilization, one that's about the relationships we have with one another and the planet that's our home. Hearing that story is part of learning how we can do better, and why it matters to all of us.

Situated Perspectives

When I was nine, my family lived in Bhopal, India, in my father's family home, for six months.

If culture is everything that you do without thinking much about why you're doing it, then our infrastructural systems, and the ways of life they make possible, are unquestionably an important part of culture. Even as a child, the differences between Canada and India—language, social norms, the deep poverty and the unignorable inequality, having strict Catholic nuns as teachers—required serious adjustment. There was also a culture shock associated with the infrastructural systems. The municipal water

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provision where we lived was on a rotating schedule, so we only had running water for an hour or so in the morning and again in the evening, and we collected it in buckets to use for bathing and flushing toilets all the rest of the time. My mother boiled and filtered the water to make it potable to digestive and immune systems that were accustomed to clean, cold, carefully treated water from Lake Ontario. We quickly learned to expect brownouts and power cuts as the growing city's electrical grid struggled to cope with the fans and evaporative coolers that were brought to bear against the summer heat.

My family moved back to Toronto in late autumn that year, and then I spent another six or so months in India when I was sixteen. That time in India made me unavoidably aware of the systems that were all working, quietly and continuously and reliably, to meet my basic needs as I was growing up. I doubt I would have noticed or thought anywhere near as much about infrastructure had I not lived in these two different places. By moving to Canada, my parents had given me a new citizenship in a country with a different set of educational and economic opportunities, alongside of which was the infrastructural birthright that underpinned my ability to access them.

Collective infrastructures are a good candidate for the most complex systems created by humans. They are planetary in scale, build on their own histories, are entangled with each other, and have impacts that extend far into the future. Their design, construction, and operation require a wide range of technical disciplines—civil engineering, obviously, but also electrical engineering, mechanical engineering, environmental engineering, and the science of systems and of networks. All of these fields incorporate not just technologies but practices, ways of thinking, doing, and building. The decision-making and funding around these systems, particularly public systems, is the province of policy, finance, and economics. Finally, as systems that require land and resources, it's impossible to extricate infrastructure from a larger history of conquest, colonialism, and capitalism and, particularly but

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by no means exclusively in the U.S., from racism and white supremacy. The theorist Timothy Morton coined the word “hyperobject” for just these sorts of systems that span multiple time scales, length scales, and social settings.

My friend Helen Macdonald’s writing about the natural environment has influenced how I think about infrastructural systems. A forest is home to trees, plants, fungi, and lichen, as well as to birds, insects, reptiles, amphibians, small and large mammals, and more, each of which is in an ongoing ecological relationship with the others. Every forest is a hyperobject, an enormously complex environment that’s shaped not just by its location, landscape, and climate but also by the history of humans in that place. If you go on a walk in the woods, what you see depends on the season and the particular path you take through it. More than anything, though, what you see in the woods depends on the eyes that you are seeing it through. A birder, a hunter, an entomologist, a soil ecologist, a real estate developer, and an artist will all see different things. Helen introduced me to Richard Mabey’s idea that the natural world can only be understood and appreciated as a result of careful, knowledgeable attention. Without the ability to describe the differences with detail and specificity, a meadow of native grasses and the pesticide-soaked monoculture of a golf course that replaces it are effectively indistinguishable. Helen borrowed Mabey’s phrase for this in an interview, calling it a “green blur.” We’ll be taking a closer look at the “gray blur” of our infrastructural landscape as we go on a walk through it, in the hope of resolving some of the details. But, as with a forest, it’s just one trail with a particular guide, and what we see depends a lot on who’s doing the looking.

Infrastructure is inextricable from culture, woven as it is into our daily life as well as our history, politics, civic life, and our visions of the future for our families and our communities. My path through infrastructural systems, and therefore what I see when I look at them, is deeply rooted in my own experiences. I’ve lived most of my life in cities in four countries: Canada, the United States, India, and the United Kingdom. I joke that as a dual

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U.S.-Canadian citizen of Indian descent, I'm a colonial three times over. While that gives me a very specific perspective on the British Empire and its infrastructural projects, growing up in anglophone North America means that England has, in turn, shaped my perspective on the world. I also spent most of my adolescence and young adulthood training as an engineer and a scientist before becoming an engineering professor. It's how I came to the world of infrastructure, and it's a big part of how I think about and describe it: as networks and systems, energy and material flows, standards and technologies, efficiency and elegance, with a similar vocabulary and perspective as the engineers who built these systems out.

But it's at least as important to my perspective on infrastructural systems that I'm the daughter of immigrants who came from a postcolonial country in the Global South and settled in a rich, industrialized country. I recognize that I'm a historical anomaly, and something of an anomaly even today. All over the planet, the responsibility for hygiene and food preparation most often falls to women. The highly gendered nature of this labor means that fetching clean drinking water or obtaining fuel to burn for cooking are daily activities for billions of women globally, especially ones who look like me, brown-skinned and middle-aged. They trade their time and the energy of their own bodies to ensure that the most basic needs of their families are met. My life, as I know it, has mostly been made possible because I had the sheer blind luck of being born into a time and place where my survival needs were met and continue to be met every day by shared infrastructure. What might our world be like if access to these systems were universal?

Cracks in the Technological Foundations

Like most living creatures, humans habituate to whatever's unchanging in our environments. The more robust and reliable our infrastructural systems are, the less we think about them, and the more time and attention we put

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into other things. When I get up in the morning, I don't think about the water coming out of the bathroom tap in the same way that I don't think about the sun rising. But unlike the sun rising, our infrastructural systems are built by humans, for humans, and all technological systems need care and maintenance. Infrastructural systems are famously boring because the best possible outcome is nothing happening, or at least nothing unexpected or untoward. But nothing happens, and nothing continues to happen, as a result of sufficient attention, specialized care, and unceasing oversight. "Nothing happening" is usually the result of careful inspection schedules, preventive maintenance, and planned replacement, all of which require resources to be devoted to what will be, at best, a null outcome. Across the U.S., decades of underinvestment in infrastructure mean that systems like transportation and the electrical grid are failing more frequently, whether small failures like delayed subway trains, potholes, or a local power outage, or catastrophic ones like a bridge collapse or a multiday blackout. Even systems that might have been adequate when they were built are failing to keep pace with changes in the larger world, whether predictable ones like population growth or new challenges like contaminants in water supplies.

Failure is relative to expectations, of course. Access to a suite of reliable, modern infrastructural systems is the global exception, not the rule. Communities all over the world, including in the U.S., have unreliable or limited access to electricity, to clean water or improved sanitation, to energy for cooking, or to reliable telecommunications. Many decades after they were first built, we have a much more widespread understanding of the injustices that can be encoded in these systems—where they are built and for whom, where they draw resources from, and who's most impacted by negative consequences, from air pollution to flooding to noise and congestion.

But the biggest threats to infrastructural systems don't come from neglect or underfunding. They are inherent. Infrastructural networks are built to move resources from place to place—atoms and bits, electrons and

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photons, people and things—and to do so reliably and continuously. The substrate that they are embedded in and traverse is the landscape. Reliability and continuity presuppose a certain stability, but the climate is no longer stable. Rather than being something that we're headed toward, anthropogenic climate change is now something that we are living through. Globally, every year since 2015 has been among the warmest years ever recorded, and we are beginning to see the effects everywhere. The western U.S. has now seen years of record-setting drought, followed by years of intense rainfall and flooding, followed by years of deadly wildfires. In the eastern U.S., there was Hurricane Sandy and dark, flooded lower Manhattan. In Puerto Rico, communities were left without power for nearly a year after Hurricane Maria. In 2020, there were so many named hurricanes that we went through the entire Roman alphabet and started in with Greek letters, with Hurricane Zeta making landfall in the U.S. in late October. Every natural disaster is the result of an interaction between a natural event and human systems, and an important measure of the severity is the degree to which infrastructural systems are affected or how quickly they can be repaired. Functional infrastructure is resilient infrastructure.

All technological systems require energy to function, and the vast majority of that energy still comes from fossil fuels. Infrastructure is also a major *contributor* to climate change. In the U.S., electricity generation accounts for more than a quarter of all greenhouse gases. Transportation accounts for another 30 percent or so, and another few percent come directly from household use, like the natural gas that's burned to warm my home and cook my dinner. In total, energy use that's mediated by infrastructural systems accounts for close to two thirds of emissions.

What all of this means is that there is no more taking our infrastructural systems for granted, anywhere. In the Bugs Bunny cartoons, Wile E. Coyote races off the edge of a cliff, looks around for a moment, realizes there is nothing below him but thin air, and *then* he falls. If infrastructure becomes most visible when it fails, we are at the exact moment when, like

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Coyote, we are looking around and seeing where our societal decisions have led us. But unlike Coyote's fall, there's nothing inevitable about what happens next.

Our Fractured Past and Our Shared Future

The hyperobjects that are our collective infrastructural systems shape not just what we actually do, day after day, as individuals and as communities, but even the possibilities for what we can consider doing. The cost of not being able to rely on previously reliable systems is unthinkably high: to have had well-functioning infrastructural systems and then to lose them is recognizably dystopian, the stuff of postapocalyptic science fiction. Which means that we can't live without them and we can't keep them as they are. What's more, we can only change them together.

But here's the thing: we have everything we need to create a different world, for everyone. We have myriad ways to harness renewable energy. It's possible to transform and rebuild our collective infrastructural systems to be functional and also resilient and sustainable. This gives us an unprecedented opportunity to rethink them for the coming century, instead of being defined by the previous one. That includes recognizing the fundamental injustices built into these systems, from the neighborhood to the planetary level, and redressing them. Fifty years ago, transforming these systems would have been an intractable engineering problem. No longer—today, the challenges we face are largely social and mostly boil down to this: How do we work together to transform these collective systems? Because the one thing we do know is that these shared systems that shape our lives, both affording and constraining the ways in which we do things, can't be changed appreciably by individual action alone.

My own relationship with infrastructure started when I was a young girl fascinated by huge engineering facilities, and I came to see and appreciate them as among the most compelling of human creations. Over the past

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decade or so, I went to stand at the edge of reservoirs, in a power station inside a mountain, on the crest of one massive dam in the desert, and on the ruins of another. I toured sewage treatment plants, walked a road that humans have followed for five millennia, stood between rows of tilted solar panels and among majestically spinning wind turbines, and walked the channel of a river through a city and down to the sea. These systems are how we care for our bodies wherever they are on the planet, and so I took my body to the systems to try to understand them. The more I learned, the more I saw how deeply our infrastructural systems were shaped by our cultures—often the best aspects of ourselves, as we committed to take care of each other, but also the very worst, literally building institutionalized racism into our highways, dams, and power systems, creating a world of haves and have-nots. I gradually began to apprehend all the ways our infrastructural systems don't serve us well—and to think more deeply about who counts as “us.” I started to recognize the degree to which they are under threat, and I learned that we have the technologies to respond to these threats, but also that doing so lends itself to a very different way of organizing our communities and our society.

It might be a truism that you can't solve a problem with the same mindset that created it, but you do still have to first recognize and understand the problem and, however you approach it, the solutions need to be on the same *scale* as the problem. Our infrastructural systems make our individual daily lives possible, but they are vast and collective, and so they can only be seen, understood, and transformed collectively. This book is intended to be a stepping stone to that transformation, but it's not a how-to manual. It's a *why-to*, and a *where-to*, manual.

Two

INFRASTRUCTURE
AS AGENCY

On a typical evening, I might drive or take the subway home to my apartment. I let myself in, turn on the lights, put down my bags, and take off my coat and shoes. I turn the stereo on and set it to play music streamed from my phone, and I head into the kitchen to make dinner. If I'm cooking something like noodles for dinner, I can get a pot from the cupboard, fill it from the tap, and set it on the stovetop to boil, and then take some vegetables out of the fridge to prepare. After years of practice, I can usually be sitting down to a hot meal in less than half an hour. Once I've eaten, I take a few minutes more to clean up, putting the waste in the trash and washing the dishes in a sink of hot water.

When I was growing up, my parents had a small Hindu altar set up in our home, with mounted posters of several multiarmed gods and goddesses in the heightened-realism illustration style that's common for these icons. As a child, I was fascinated by the warrior-goddess Durga, who was depicted with weapons in many of her hands and riding a tiger that's trampling a demon under its paws. Despite what those terrifying attributes would suggest, Durga isn't associated with only war and destruction—she's also a goddess of