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CAMILLE SEAMAN
The Semi Truck & the Mothership, Bartlett, NE, 16 June 2014

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A more integrated and systemic approach is needed to ensure the nation's resilience in the face of a changing climate.

The United States is at an infrastructural crossroads. First, the climate is changing faster than built infrastructure and the institutions that manage and maintain it. Recent extreme weather events highlight the precarious state of the nation's infrastructure and the ability of cities to adapt to climate change. After the nation in 2016 broiled through its hottest summer on record, 2017 began with one of the wettest winters on record for California and the Pacific Northwest. The 2017 hurricane season proved to be the most devastating and costly in the nation's history. Hurricanes Harvey in Texas and Irma in Florida inflicted as much as $290 billion in damages. In the past 60 years, there has never been an Atlantic hurricane as intense as Maria was over the US territory of Puerto Rico. Two months after the hurricane, fewer than half of Puerto Rico's 3.4 million residents had regained electric power. According to some estimates, Maria may have set the Puerto Rican economy back by a quarter century in just 12 hours. And adding to the list of miseries, a series of wildfires starting during volatile weather conditions in October devastated large areas of northern California and claimed at least 43 lives.

Second, US infrastructure—in such diverse sectors as transportation, energy, and water—needs billions of dollars of investments to merely maintain current service levels, according to the American Society of Civil Engineers. Aging infrastructure, based on decades-old assumptions about societal needs and environmental conditions, must continue to deliver services to communities with changing needs, demands, technologies, and values. Combined sewer-storm water systems, for example, were the standard for many cities to manage wastewater and storm water in the late 1800s and early 1900s. However, due to changes in public health and environmental concerns since these systems were built, most cities now recognize that the cost savings of combining these systems is outweighed by the hazards created when sewage overflows into waterways during heavy precipitation events. As a result, cities such as Portland, Oregon, and Philadelphia have had to spend millions of dollars over the past 25 years to retrofit their combined systems to comply with the US Clean Water Act and other environmental regulations. As cities and states work to deliver services, they must also deal with the legacy of these existing outdated systems.

Finally, over the coming years there may be massive investments in the nation's infrastructure. Cities, states, and regions will continue or ramp up efforts to maintain and retrofit infrastructure to deal with increasing demands, changing populations, and the specter of climate change. The states and regions affected by recent extreme events will recover and rebuild. Meanwhile, the federal government has proposed to invest up to $1 trillion in infrastructure while at the same time, according to an August 2017 executive order, reducing requirements for federal spending on infrastructure to account for climate risks.

How cities, states, regions, and the federal

The Big Cloud

Images by Camille Seaman

Camille Seaman has been chasing storms since 2008. It started when her daughter Tala was watching the television show *Storm Chasers* at their home in the San Francisco Bay Area and said, "Mom, you should do that." Three days later, she was stalking a giant supercell thunderstorm in Kansas. The project is a natural continuation of her exploration of subjects in nature that have the ability to illustrate the interconnectedness of life, an exploration which began many years earlier with her photo series *The Last Iceberg.*

Supercells are the rarest type of thunderstorm and have the potential to be the most severe. They are capable of producing tornadoes and grapefruit-sized hail—although only 2% actually do. They can grow up to 50 miles wide and can reach up to 65,000 feet into the atmosphere. Seaman describes the tactile experience of storm chasing: the warm, moist wind at her back; the smell of the earth; the charged particles in the air; and the eerie greens and turquoise blues in the clouds. What excites her most, she says, is the movement of the clouds as they swirl, spin, and undulate. She is taken by the stunning beauty and the destructive power of storms, which she describes as "lovely monsters."

Camille Seaman is a TED Senior Fellow whose 2013 TED Talk on her photographs of supercell storms has garnered more than 1,600,000 views. Her book *The Big Cloud* will be released in 2018, and her previous book *Melting Away: A Ten-Year Journey through Our Endangered Polar Regions* was published in 2014. She has received a National Geographic Award, and her photographs have appeared in publications including *Time*, the *New York Times*, and *Men's Journal*. Seaman's first solo exhibition was at the National Academy of Sciences in 2007–2008.

CAMILLE SEAMAN
Above: *The Colapse II, South Dakota, June 2008*
Opposite: *The Lovely Monster 19:17CST, Lodgepole, NE, 22 June 2012*

CAMILLE SEAMAN
Deluge of Rain in Haswell, Colorado, 29 June 2013

government navigate these key issues will determine the path taken at this crossroads. Will it be a path that uses the technologies and climate conditions of the twentieth century to design for tomorrow? Or one that rethinks how infrastructure is designed, managed, and maintained for the technologies, societal needs, and hazards of the twenty-first century?

We examine some of the underlying social, ecological, technical, and institutional issues that often seem to set infrastructure up for failure. We focus primarily on failures in the context of climate change and extreme weather events. We review several cases with an eye toward the lessons that policy-makers, infrastructure engineers, and managers can glean to conceptualize, design, build, and maintain the infrastructure of the future. And we then explore emerging innovations that provide insights into a more resilient future.

Learning from failures

Climate change and extreme weather grab headlines and present a fundamental challenge to the ability of infrastructure to protect communities. But beneath the seemingly endless cascade of catastrophes lie consistent, systemic failures in current approaches to infrastructure. One common failure is an overconfidence, bordering on hubris, in the ability to tightly control complex social and ecological systems through the management of technological systems. Another is the failure often associated with managing interdependent infrastructure systems. And there are failures in the ability of institutions that manage infrastructure to generate, communicate, and utilize knowledge. This list of failures is not exhaustive, nor is it meant to be. Instead, the discussion focuses on these consistent drivers of infrastructure failure that cut across multiple infrastructure types, extreme event categories, and jurisdictions.

To reveal and understand these drivers, we view infrastructure as not just the built hardware. It is also the institutional rules, norms, knowledge, and standards that design, maintain, and manage the infrastructure; the social norms and expectations about the use of services delivered by infrastructure; and the ecological systems that are designed or managed, or both, by infrastructure. Infrastructure, then, comprises not simply technical systems, but interconnected social, ecological, and technological systems.

Control of complex systems. In his 1989 collection of essays, *Control of Nature*, John McPhee examines how humans attempt to exert control over natural systems. He describes efforts to fend off lava flows in Iceland and curb landslides to make way for development in greater Los Angeles. But it is in "Atchafalaya," an account of the US Army Corps of Engineers' actions to prevent the Mississippi River from changing its course, that he most effectively captures the futility of human efforts to control complex systems.

McPhee illustrates how the Army Corps, with support from local politicians and communities, designed the Old River Control Structure to regulate the flow of water from the Mississippi River to the Atchafalaya River. Without this structure, the flow would increase over time, eventually resulting in the Mississippi changing its course. Needless to say, this would be inconvenient for urban and rural communities, including New Orleans, that rely on the river and its various engineered structures for irrigation, flood control, and commerce. As McPhee notes, "for nature to take its course was simply unthinkable."

Engineers designed the Old River Control Structure and other flood control systems in the region to handle certain degrees of flooding, calculated using historic precipitation data and water flow rates. Yet as geologists and hydrologists know, the Mississippi River and Delta comprise a complex and dynamic system that has evolved and meandered over time. Attempts to control the system have "harnessed it, straightened it, regularized it, shackled it," as McPhee said. When elements of the system fail, however, the results are catastrophic, as demonstrated during the flooding events along the Mississippi in the 1990s and with Hurricane Katrina in 2004. Dams along the river system also starve the Mississippi River Delta of silt that is needed to replenish the wetlands, an invaluable source of coastal storm surge protection. In addition, sea level rise further erodes the wetlands. The conclusion of McPhee's essay still rings alarmingly true: "It's a mixture of hydrologic events and human events. It's planned chaos."

This story illustrates how infrastructure has been traditionally designed to manage environmental hazards or deliver a narrow set of services. Society builds infrastructure to remain structurally or functionally sound up to a particular severity of event, such as a 1-in-100 year or 1-in-500 year intensity rainfall. This so-called fail-safe approach to infrastructure design has led to large and often oversized infrastructure, with little to no thought given to how to manage the consequences of failure. Such designs also often focus on a single service (such as flood control) at the expense of other potential services (such as thermal regulation, recreation, and coastal storm surge protection). With the uncertainty that climate change imposes on the frequency and intensity of extreme events, this risk-based model of infrastructure design needs to be questioned. The barriers against building larger infrastructure may be prohibitive and the potential for failure is likely to increase.

California experienced a record wet winter in 2016-2017, receiving more than 400% of the average amount of precipitation. Cities and towns from Humboldt in the north to Los Angeles in the south were flooded, sinkholes swallowed cars, residents were evacuated, and roads and schools closed throughout the state. These extreme precipitation

CAMILLE SEAMAN
Purple Lightning, Canadian, TX, 22 June 2014

events were punctuated on February 12, 2017, when 188,000 people around the city of Oroville were ordered to evacuate their homes because the emergency overflow spillway on nearby Oroville Dam appeared to be failing, threatening to flood local communities. This marked the first time the spillway had been used since the dam's construction in 1968. Fortunately, the dam eluded a massive failure, but the incident underlined the degree to which a fail-safe approach to infrastructure seems increasingly tenuous as design conditions are more routinely exceeded in a changing climate.

Interdependence of infrastructure. Although it is clear that infrastructure components are interdependent, they are often designed, managed, and maintained as separate entities. The transportation bureau manages the transportation system. The storm water bureau manages storm water. And so on. Yet the extent of these interdependencies is likely increasing, creating complexities that are inimical to the current understanding of how perturbations cause large-scale outages. It is well established that the services provided by one infrastructure are required for others to function (for example, power generation requires water, and traffic signaling requires electricity). What is less well known is how the decades and centuries of building and interconnecting infrastructure, embedding new hardware, and lately connecting with information and communication technologies have resulted in a kludge of unpredictability. The 2011 Southwest blackout, for instance, shows how vulnerabilities can propagate across infrastructure. What began as a minor outage in Arizona cascaded to Mexico and Southern California over the course of 11 minutes. The blackout ultimately left roughly seven million people without power. It resulted in loss of transportation services as well as water treatment capacity.

More recently, the destruction of Puerto Rico's energy system by Hurricane Maria not only resulted in the largest power outage in US history, but it also had compounding effects on other critical infrastructure necessary for relief efforts after the disaster. The island's entire communication infrastructure, including cellular networks and telephone lines, broke down, rendering emergency managers, government agencies, and Federal Emergency Management Agency (FEMA) officials unable for days to share information about the storm's damage and move rapidly to implement relief efforts on the ground. The island's main airport could not function without power or communication, and thus for days it could not receive airplanes with shipments

CAMILLE SEAMAN
The Beast It Grows & Consumes All Daylight, El Reno, OK, 31 May 2013

CAMILLE SEAMAN
Chasing a Mothership in Minnesota, Browerville, MN, 20 June 2014

and people could not leave. The power outage also affected the island's ability to maintain basic services for the population, such as providing clean water, maintaining life-support health equipment, and pumping flood waters.

Part of the vulnerability of the island's energy grid was its own interconnectedness and lack of redundancy. The centralized electric grid ran almost entirely on fossil fuels, which are entirely imported, and electricity was transmitted through a decaying system of towers and distribution cables. Maria's 155-mile-per-hour winds destroyed more than 200 transmission towers and hundreds of miles of transmission lines, as well as thousands of distribution lines that connect individual households and businesses to the grid. Before the hurricane, the agency responsible for the governance of the electricity system, the Puerto Rico Electric Power Authority, was in great debt (it owed $9 billion of Puerto Rico's more than $74 billion debt) and could not maintain the grid or have backup systems for redundancy, especially for more remote rural areas. The only backup that residents and businesses had were electric generators that run on gas or diesel, but these fuels had to be imported from the US mainland and transported from shipping ports to gas stations. More than a month and a half after the hurricane, only 42% of the power generation capacity had been restored, leaving Puerto Ricans intensely aware of how dependent their resilience is to this infrastructure.

Knowledge systems. The effects of extreme weather events on infrastructure have also exposed a number of failures in institutional knowledge systems: the organizational practices and social structures that produce the information, data, and expertise on which engineers, designers, and decision-makers rely. A post-Hurricane Katrina report by the American Society of Civil Engineers in 2007, for example, showed how the combination of inadequate knowledge and unfortunate choices at all levels of responsibilities led to the engineering portion of the disaster, including miscalculations on the size of the levees and flawed models of variability of soil conditions in New Orleans. The complications of multiple and overlapping political and legal

CAMILLE SEAMAN
In Pursuit, Browerville, MN, 20 June 2014

jurisdictions, and the weak institutional authority of the New Orleans Hurricane Protection System, led to a failure in the detection of emerging vulnerabilities in the levee structure.

To cite another example, the Phoenix metropolitan area in 2014 experienced a 630-year rain event in August followed by a 984-year event in September, the latter the highest amount of precipitation ever recorded for a single day. Both events caused flooding of Interstate 10 and major traffic disruptions. The flooding was not the result of the breakdown of hardware. Instead, the technology functioned as it was designed to do. The pumps, which were designed for much lower intensity rainfalls, automatically turned off to protect themselves from overheating. These design conditions are set through a number of processes within the institutions that manage infrastructure, but in these cases they failed to take into account the most extreme weather events.

Inefficiencies in the knowledge systems supporting the analysis and communication of risk distribution in urban areas also limited the ability of city officials in Houston and San Juan to appropriately communicate the risk and reduce the vulnerability of their populations to extreme weather variability. Hurricanes Harvey and Maria revealed how little awareness people had of their own vulnerability. Homeowners living in flood zones were not aware of their exposure to high flood risks. Though most people in these areas were likely aware of their exposure to flood events that could occur during a 100-year flood, because they are required to purchase flood insurance from FEMA, the past hurricane season brought multiple 500-year floods. Furthermore, for many cities, including San Juan, the FEMA flood maps that determine where flood hazards are located are outdated, and thus many residents were not aware of the higher risks they were facing with these extreme events. Similarly, many homeowners in Houston did not know they had bought homes in marshlands that were intended to flood when the bayou system flooded.

A recent analysis by the US Department of Homeland Security revealed that 58% of FEMA flood maps are either inaccurate or out of date. In the wake of Superstorm Sandy in 2012, the flood maps for New York City were famously exposed as woefully outdated, with the most recent update coming in 1983. Yet even if the flood maps were 100% accurate and up-to-date, they are based on retrospective data and still would not account for future conditions such as climate change. These seemingly mundane codes and standards carry embedded assumptions about climate and weather conditions that form the DNA of the nation's infrastructural systems that support modern life.

These examples show how infrastructure failure is a complex process that involves the breakdown of not only physical hardware but also the institutions that manage the hardware, as well as post-disaster recovery.

Toward more resilient infrastructure

Given the uncertainty of climate change, the degraded status of US infrastructure, and the potential for large investments in rehabilitation and new construction, the processes that society uses to design infrastructure should be fundamentally questioned. Climate change can introduce so much uncertainty that simply shifting probability distributions for future events and continuing with standard practice is likely no longer sufficient. At some of the more severe ends of climate forecasts, the infrastructure components that would need to be designed are potentially so large, costly, and aesthetically unpleasing—and possibly technically infeasible to construct—that current forms of infrastructure in some situations may be obsolete. New models are needed that balance fail-safe designs with other resilience strategies, including green infrastructure and safe-to-fail systems that do not promise absolute protection but result in limited damage when they do fail. Green infrastructure systems have been used across the nation to help retain water and thereby reduce the potential for flooding. New models for infrastructure will be need to be smarter about recognizing the consequences of failure, allow infrastructure to fail, and manage the consequences of failures.

Approaches, old and new, to urban flooding provide some promising examples to building more resilient infrastructure. In the 1960s, a controversy emerged between the community of Scottsdale, Arizona, and the Army Corps of Engineers about how to best manage flooding in a rapidly urbanizing area along the Indian Bend Wash. The traditional approach, advocated by the Army Corps, was to turn the wash into a concrete-lined channel. Think of the Los Angeles River in the famous *Terminator 2* scene that has T-1000 driving a semi-truck in pursuit of Jack Connor on a dirt bike. The Scottsdale community successfully fought the Army Corps to design and build an 11-mile-long greenbelt—a series of parks, ponds, and, of course, golf courses (this is Arizona after all)—that allows the wash to flood without damaging the surrounding property.

This type of safe-to-fail design that allows for some flooding has been adopted elsewhere as well. The Netherlands, which is precariously located below sea level and has historically done as much as possible to prevent flooding, recently implemented what it calls the Room for the River program. Instead of building ever bigger levees to hold back water, the Netherlands manages the consequences of failure by letting farmers use the land along flood-prone waterways and reimbursing them when crops are damaged. US cities are also giving more room for flooding along rivers or coastlines. After Sandy, New York City offered buyouts to Staten Island residents on the shoreline whose homes were destroyed or threatened. And in Portland, Oregon, the Bureau of Environmental Services and Portland Parks and Recreation collaborated to purchase the homes of residents located in a flood-prone area along Johnson Creek, a tributary of the Willamette River. This area on the east side of the city had flooded consistently over previous decades, including the Great Flood of 1996. The city restored this area of the floodplain in 2012 to create the Foster Floodplain Natural Area, which allows the area to flood and thereby helps to alleviate flooding further downstream.

These examples demonstrate how infrastructure changes require institutional and knowledge systems changes. For example, knowing how to design ecological functions such as storm water regulation or thermal regulation through the planting of trees and other plants is not only a technical or ecological issue. It also necessitates new forms of coordination between governmental organizations responsible for delivering different kinds of services with different sources of funding. Storm water management bureaus, for instance, are often allowed to spend ratepayer monies only on storm water benefits. As cities look to green infrastructure for thermal regulation to ameliorate urban heat island issues, they must also overcome institutional barriers to designing services.

Emerging data and communication technologies can also help cities get smarter about infrastructure design and maintenance. Advocates of initiatives such as "smart cities," which rely on big data analytics, and the "internet of things," which

CAMILLE SEAMAN
The Hightower at Night II 20:53CST, Big Springs, NE, 22 June 2012

harnesses advanced digital tools and devices, view digital technologies as a connected infrastructure of data collection, use, and interpretation that can optimize the operations of a city toward smarter economies, environmental practices, and governance. For instance, early warning systems for coastal flood hazards that include a network of data sensors throughout the city can help flood and emergency managers better understand how flood waters are distributed and what people and places are more at risk. Whereas initiatives to create smart cities have the potential to help communities anticipate events and develop adaptation strategies to climate change, their effectiveness rests on advances in a multiplicity of technological as well as cognitive, social, and institutional factors that are embedded in these smart systems' technologies. Nevertheless, if used in meaningful ways, these innovations in data systems and digital technologies have the potential to help protect people, improve their quality of life, and increase infrastructure resilience to climate change. Rather than viewing such technologies and data analytics as technological fixes, they can be seen as serving as opportunities to upgrade decisions when appropriately embedded in institutional decision-making contexts.

Puerto Rico may provide a case in point. As state and federal agencies are moving quickly to fix the energy grid and deliver power to millions of people, many policy-makers, politicians, energy experts, and residents recognize that this will not be a long-term solution. Instead, they are viewing this breakdown of the infrastructure as an opportunity to reconstruct the system using more sustainable and clean energy options. After seeing—and in some cases experiencing firsthand—how fundamental energy is for the resiliency of the island, local and national leaders are calling for strategies to phase out the twentieth-century centralized power model and move toward more resilient alternatives such as solar micro-grid technologies. Such energy transformation will require not just new ways to redesign the technological aspects of the infrastructure, but innovations in the governance of the infrastructure. In this light, Luis A. Avilés, a former chair of the island's electric power authority and current law professor at the

University of Puerto Rico, has called on Congress to design and implement island-centric energy policy and economic incentives to ensure that Puerto Rico and other US territories can get the energy they need while not being so dependent on the mainland.

These innovations display a consistent ability to look beyond narrow technical design decisions to broader rethinking about the social, ecological, and technological means and arrangements that provide services to communities. To build more resilient infrastructure, cities, states, and regions will also need to reconceptualize what services they provide, to whom, and how they arrange social, ecological, and technological systems to do so.

Moreover, decisions today will create a new infrastructural legacy that will last well beyond today's problems. Evidence continues to accumulate that many components of infrastructure are unable to cope with more extreme events and that building bigger and stronger simply may not be feasible. The inability of infrastructure to handle climate extremes is rarely an issue of poor engineering or faulty technical designs. Instead, it's that infrastructures were designed for different weather patterns as well as different social values and demands. And into the future, these events are expected to become more frequent, intense, and unpredictable. Demands will increase and values will surely evolve. This future should give pause to question whether the models of infrastructure that scientists and society have come to rely on are sufficient going forward.

Resilience must be understood as the capacity of institutions and the infrastructure they oversee to adapt to unpredictable and changing conditions, not just in terms of the infrastructure hardware, but also in terms of the people who rely on the systems and the institutions that manage them. Both the failures and positive innovations we have discussed here highlight the need to take a broader view of infrastructure as dynamic systems in turn comprising interconnected social, ecological, and technological systems. As such, so too must society look for ways to foster resilience across these systems.

Toward that end, we suggest the following actions:

- *Move from a risk-based to resilience-based approach*. The current strategy is one where failure of infrastructure is not allowed. Infrastructure managers must be trained to think about failure as a possibility, how to manage failure (that is, reduce the consequences), and how to evaluate the costs and benefits of safe-to-fail strategies. Although the current federal administration is not requiring climate change to be considered in infrastructure design, doing so is unavoidable. It is now an opportune time for professional societies, cities, and states to step up, establish guidelines, and share knowledge.
- *Require knowledge systems analysis*. Assumptions about future conditions are embedded at every level of infrastructure design and maintenance. Yet rarely are systemic efforts undertaken to analyze how assumptions about future weather and climate may generate vulnerability. Such a position is becoming increasingly untenable. Moody's Investor Services, for example, recently issued a report stating that the credit rating agency will assess a city's climate preparedness when accounting credit risks. Those institutions responsible for managing and maintaining infrastructure must critically evaluate how assumptions about the future of climate and weather are embedded in decision-making, policy, codes, and standards.
- *Enhance institutional integration and coordination*. To address the interdependence of infrastructure systems, the institutions that build, manage, and maintain them must explore new models of institutional design**.** The institutions that now manage infrastructure must continue to do so, with the knowledge and depth they have of the systems. But there remains a need for new forms of organization that are able to manage interdependencies—such as regional governmental entities—and integrate efforts to manage infrastructure and enhance resilience. Pavement engineers and nuts-and-bolts knowledge of hydraulics will remain critical, but so too there will be a need for new competencies that understand complexity and interactions. Most important, capabilities will be required for working within these interdependent systems that acknowledge their complexities and the growing possibilities that we cannot predict what might happen when things are perturbed. That's a fundamentally new approach.

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