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Infrastructure resilience to navigate increasingly uncertain and complex conditions in the Anthropocene

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Infrastructure are at the center of three trends: accelerating human activities, increasing uncertainty in social, technological, and climatological factors, and increasing complexity of the systems themselves and environments in which they operate. Resilience theory can help infrastructure managers navigate increasing complexity. Engineering framings of resilience will need to evolve beyond robustness to consider adaptation and transformation, and the ability to handle surprise. Agility and flexibility in both physical assets and governance will need to be emphasized, and sensemaking capabilities will need to be reoriented. Transforming infrastructure is necessary to ensuring that core systems keep pace with a changing world.

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ACCELERATION, UNCERTAINTY, AND COMPLEXITY

Infrastructure are at the center of three trends: accelerating human activities and impacts, increasing uncertainty in social, technological, and climatological factors, and increasing complexity of the systems and environments in which they operate. These trends are interrelated and have profound implications for infrastructure -- for the engineered systems with their physical assets that deliver basic and critical services, such as traditional transportation, energy, water, and communication networks; for the institutions that provide the rules and norms that structure individual and collective action by allocating responsibilities and rights, imposing constraints, and creating incentives that support these physical systems; and for education (including universities, job training, continuing education, etc.) that forms the basis for how infrastructure designers, managers, decision-makers, and regulators make sense of their systems and the environments they must operate in. Traditionally, infrastructure systems emphasize components, processes, and sensemaking for conditions of certainty, resulting in rigidity that is often inimical to change. While humans, and the institutions and systems they design, can adapt to new conditions given enough resources and time, conditions in the Anthropocene are changing so rapidly that they appear to exceed the adaptive capacity of our designed systems[1].

Since around 1950, the exponential growth of human demand for infrastructure services, and the corresponding impacts on the environment starkly illustrate the Anthropocene. The rate and scale of change is seen with the Great Acceleration Curves[2] – showing accelerating trends across several critical human impacts – raising questions of how emerging and disruptive technologies, inequity, climate change, ideological extremism, and hyper-connectivity appear to be creating environments of deep uncertainty. Here we use the term environment broadly, to describe the confluence of social, ecological, and technological operating conditions. Accelerating and increasingly uncertain forces add complexity to infrastructure systems that are already complex in nature[3], resulting in conditions where infrastructure systems may struggle to remain viable into the future. The impacts on infrastructure are powerful and multipolar, and create a context where the current ways of framing, designing, building, operating, maintaining, and transitioning human engineered systems appear increasingly unable to cope.

The Great Acceleration Curves are indicators of the non-linear effects brought with technological and infrastructural change as well as institutional capabilities, framed by inventions like the Internet, natural disasters like Hurricane's Katrina and Sandy, and major events like COVID-19. Of the 12 indicators tracked in the Great Acceleration Curves, at least seven (energy use, fertilizer consumption, dams, water use, paper production, transportation, and telecommunications) are directly related to infrastructure. In much of the post-industrial world, infrastructure complexity has grown to the point where the emergent characteristics of the systems are difficult, if not impossible to predict[3]. Furthermore, the rigidity with which the technologies and institutions are designed appears to be decoupling from the environments in which these systems operate[4–6]. The physical assets, institutions, and educational practices of infrastructure focus on minimizing variability and creating stability. In the Anthropocene, infrastructure are poised to be repeatedly shocked by the rapidly changing environments in which they must reliably deliver services.

While we focus broadly on the many variables that affect complexity, uncertainty, and acceleration, the recent COVID-19 pandemic highlights how poorly prepared our infrastructure systems are for shocks in complex world. Unlike many other hazards, (e.g., extreme weather events, disrepair, or terrorist attacks), the COVID-19 pandemic has indirectly "attacked" infrastructure: the assets were largely structurally unaffected, but envelopes of normality were shocked with rapid demand increases (e.g., telecom, broadband, logistics and delivery services, healthcare) and decreases (e.g., personal transportation, public transportation, air travel, certain foods). COVID-19 has resulted in immediate impacts to human and natural systems, and the aftermath is likely to have long-term impacts on infrastructure

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investment, global health, and environmental indicators[7]. It is likely that social distancing and health impacts will affect our ability to maintain and operate systems at levels approaching previous conditions as designed and intended. The pandemic will lay bare the capability (or lack thereof) of infrastructure systems to adapt and respond to this and other shocks–whether from climate change, Artificial Intelligence, or civilizational conflict warfare. Some systems may be able to quickly add capacity to meet new demands and expectations of the infrastructure. Some will deploy innovative practices to keep basic operations going and triage their inefficiencies into the future. Some will not survive in their current form or will require propping up, and all of these impacts will not be uniform within and across countries–possibly exacerbating existing inequities. COVID-19 highlights the challenges that infrastructure face when they are structured to operate under assumptions that what they do and how quickly they do it will occur within a stable and predictable envelope of external variability, whether these variations are environmental (as much research has focused on) or anthropogenic (as the impacts from COVID-19 demonstrate). The design, provision, and operation of infrastructure systems appear to require major adaptations for the Anthropocene, yet few research and efforts exist to understand and guide this change.

In the midst of a changing environment resilience research has surged[8,9]. Whether this surge at a time when complexity is increasing is a coincidence or a structured response remains unclear. But what is clear is that resilience appears well-positioned to help support the transitions of human and infrastructure systems into the future. Going forward, we attempt to frame the need for infrastructure in the Anthropocene as one that can be supported by resilience theory, towards building capacities to adapt and transform. In doing so, infrastructure will need to become agile and flexible in the face of accelerating and uncertain environmental conditions, and shift from models that assume stability (and therefore control) to unpredictability. They will need to become knowledge systems capable of making sense of how their systems and environments are changing.

INFRASTRUCTURE SERVICES IN THE ANTHROPOCENE

A rapidly changing environment—inclusive of the broad social, ecological and technological systems and context in which our infrastructure exist—combined with accelerating integration of cyber-technologies into physical systems (including massive information flows and access, processed by Artificial Intelligence) is poised to change how infrastructure are designed and services delivered. Modern day infrastructure, and the institutions that govern them, are largely designed for a particular and often long-term demand scenario (e.g., roadway capacity for automobility needs for the next two decades). These scenarios often assume that past weather extremes, technologies and operating conditions are similar to what we will experience in the future, and that services themselves will be used relatively predictably into the future. This thinking has generally worked for decades because the conditions under which we provide services have been changing slowly and within factors of safety in design. The result is that basic and critical services are delivered by technologies and institutions that emphasize stability, and that there is a preference for systems that maintain their core performance for decades as they meet functional requirements[10,11]. Rigid systems (both in terms of assets and institutional processes), as they are designed today, appear less capable of adapting quickly to a rapidly changing environment.

There are many indicators that the services that infrastructure deliver will change. Humans will always need energy and water, for example, but the particulars of how they and other basic services (such as mobility and information access) are demanded may shift dramatically in an information rich world with technologies that are markedly different than the past century. Additionally, new demands for basic or critical services may emerge, as the world has seen over the past few decades with access to the internet and the advantages it enables[12]. How we think about services into the future may change. For example, consideration and inclusion of esthetics, well-being, accessibility, and equity may become increasingly important aspects of infrastructure service provision. And as control is yielded to cyber-technologies, and away from people, the implications for demand are enormous. Smart home devices are controlling how water and energy in buildings are consumed[13–19], networked devices are increasingly deciding irrigation and electric vehicle charging schedules[20–26], and increases in new mobility services (particularly ridesourcing vehicles and micromobility) are enabled by pervasive smartphone adoption[27]. And this is just today, at the infancy of the digital age. While we are starting to understand and grapple with the possible implications of a future of radical new mobility (for example) enabled by automated, connected, shared, and electric mobility controlled by cloud software utilizing Artificial Intelligence to make systematic decisions, more radical changes are beyond our ability to predict. For example, how might Artificial Intelligence steer demand for services, infrastructure implementation, and urban planning[28,29]?

Infrastructure systems have become more complex and the institutions that govern them appear poorly equipped for this new paradigm. Many sub-systems of infrastructure can be considered *complicated* in that right answers exist and an expert is able to identify them (cause-and-effect relationships are clear and the emerging characteristics of the sub-system are predictable). However, infrastructure at a macro scale now appear to exhibit unpredictable emerging characteristics, i.e., they are *complex*. This complexity results from a large number of interacting (at times non-linear) elements, a dynamic system (with history) that in aggregate arises from circumstance, and agents and the system constraining each other[30–33]. Layering of technologies over decades that creates opaqueness in sub-system logic, interdependencies and feedback loops, and self-organizing behavior have resulted in systems whose dynamics and behaviors are beyond the comprehension of any individual or governing institution[3]. Decades of policy changes and government decisions that affect public-private relationships, federal and state cost sharing, and public engagement are a source of this complexity. Yet the management of these systems largely employs processes associated with complicated systems, assuming that the system is predictable and therefore controllable[34]. Here again, COVID-19 highlights the unpredictability and vulnerability of these systems. In the immediate aftermath of COVID-19 related closures, traffic volumes reduced by up to 40-65 percent[35] causing substantial reductions in revenue for transportation departments. These reductions have cascaded into reduced construction and maintenance programs and may ultimately accelerate the worsening of transportation networks' rigid assets. Public transportation systems and airports face similar financial pressures due to fewer passengers, exhibiting the fragility of these infrastructure systems to rigid operating assumptions.

While engineering-based centralized gray infrastructure technologies and supporting institutions have dominated service provision for over a century, emerging technologies, changes in extreme events, and concerns for reliability (due to aging and growing complexity) are driving new thinking on infrastructure form and function into the future. Hybrid cyber-physical, centralized-decentralized, and gray-green forms have captured our attention with interest focused on augmenting existing capabilities while at the same time addressing environmental and social tradeoffs that have persisted with conventional infrastructure technologies[36,37]. The rapid acceleration and integration of cyber-technologies into physical systems is creating a new cognitive infrastructure, with implications for warfare, and how we understand and interact with the world[38,39]. While conventional technologies still dominate and show no sign of significantly releasing their grasp anytime soon, forces are converging that appear well-positioned to upend today's infrastructure technologies, governance structures, and perceptions.

RESILIENT INFRASTRUCTURE

The development of resilience theory is accelerating at a time when complexity has grown and our ability to manage and make sense of human systems is fragile. Resilience, originally a latin verb (resilire: to jump back), has been used since Classical times to describe movement and rebound in both physical objects and human emotion. It first appeared as a descriptor in scientific domains in 1625, when Sir Francis Bacon is credited with using the term to describe the behavior of echoes. Soon thereafter, it was used to describe the mechanical action of watches and other machine-driven objects and systems. By the nineteenth century, resilience was used to describe the behaviors of steel beams as well as the design of warships[40]. By the 1950s it made its way into psychology, and by the 1960s engineers and physicists were using the term to describe "the capacity of a material to absorb and unload energy[9]. It was the hallmark work by Holling that framed resilience in the context of complex adaptive ecological systems towards describing ecosystem dynamics around equilibrium[41,42]. Following, the concept became pervasive in the social sciences[43], later leading to social-ecological resilience theory[44–47]. The term "engineering resilience" was used in ecological and socio-ecological literature to draw distinctions between static and dynamic system management practices with the latter embracing adaptation and transformation. Despite recent attempts to integrate these perspectives for infrastructure, most research from the engineering community still focuses on rebound and robustness as the two predominant views of resilience[44,48,49]. Attempts to integrate approaches are rare and center on work from the resilience engineering field, where there is deeper consideration of adaptation and transformation of infrastructure and its services within broader social, ecological, and technological systems[50,51].

In the emerging resilience framing landscape, the apparent convergence of several commonalities may be useful for addressing complexity. Due to the universality of issues like globalization and changing natural and anthropogenic hazards, numerous articles focusing on resilience span across many disciplines[52]. Though a complete review is beyond the scope of this paper, existing perspectives of resilience in single or multi-domain disciplines reveal several common perspectives. First, resilience has become viewed as an action that systems perform rather than an equilibrium or endpoint to aspire toward[53]. Second, resilience as an action requires adaptive (ability to learn, combine knowledge, adjust responses) and transformative (create new systems when the old are untenable) capacities[9]. Third, in the context of the Anthropocene, resilience is increasingly framed in terms of the interplay of social/governance, ecological, and technological/infrastructural domains[50,54]. The three domains are interrelated, and any effort towards resilience must recognize and leverage the capabilities, limitations and co-dependencies of each. Engineered infrastructure resilience theory has recently started coming to terms with the limitations of change resistance and bouncing back as exclusive strategies[51,55]. While the resilience framing debate is far from mature, the overlapping principles are promising, and their convergence may not be coincidence. As shifts from complicated to complex thinking around coupled human and natural systems take place, resilience is well-positioned to help us navigate the changing environments.

Resilience in engineered infrastructure research has so far heavily focused on challenges related to extreme events, but appears to be increasingly adopting thinking from social and ecological systems resilience theory. Concern for climate change impacts coupled with aging assets (in post-industrial regions) have resulted in a spike in research and policy around infrastructure resilience. Efforts span characterizing vulnerability[56–58], quantifying resilience[59], and rethinking the relationship between infrastructure and the natural environment[60], to name a few. Woods, for example, describes Graceful Extensibility (being prepared to adapt to handle surprises) and Sustained Adaptability (the ability to adapt to future surprises as conditions evolve) as strategies that are necessary when boundary conditions -- how systems are designed to handle disturbances and variations -- are exceeded[61]. Yet both Graceful Extensibility and Sustained Adaptability remain difficult to implement, as most infrastructure decisions are capital intensive and initial design decisions can be effectively locked-in for multiple decades or longer. What remains unclear is whether the engineered infrastructure communities are sufficiently recognizing that climate change represents just one of the many accelerating and uncertain forces that will define the future. The concept and practice of resilience also needs to expand to ensure historical inequities and structural racism embedded in infrastructure systems are not further locked into place through hardening of existing systems[62]. It is imperative that, under increasing complexity and external pressures, resilience decisions consider and address equity implications and the impacts on vulnerable populations.

TRANSFORMING INFRASTRUCTURE FOR COMPLEXITY

To identify more resilient pathways for infrastructure systems to engage with complexity, researchers, practitioners and decision-makers need to create opportunities for rethinking traditional technologies, governance models, and educational outcomes. Historically, infrastructure were used to reduce and control social and ecological complexity, often by reducing variability, using socio-technical systems to deliver a set of eco-technical services to communities. Indirectly, infrastructure has increased the complexity of its operating environment by enabling non-linear growth in demands for infrastructure and perturbing ecological systems. In the Anthropocene the models and organizational forms that we use to plan and control no longer align with the socio-eco-technological complexities we have created[63]. Opportunities must be created to navigate complexity in different ways. But opportunities will only be realized if we accept that infrastructure systems must change, and guide this change appropriately. Here, we attempt to describe changes across technologies, institutions, and education that are needed to reposition infrastructure in the Anthropocene. We broadly refer to the goal of this repositioning as sensemaking, the process of giving meaning to how the environment is changing, and changing technologies, governance, and education at a fast enough pace to remain viable[63,64]. This requires a realignment of infrastructure systems – their technologies, institutions, and educational goals – for complexity.

The technologies that make up the core of infrastructure assets must transition to agile and flexible configurations that allow for quick changes in response to changing environmental and demand conditions. Assets continue to be designed for rigidity under assumptions of relative environmental stability. At the same time, the explosion of cyber-technologies into physical assets is creating complexities, and new paradigms for infrastructure[38,39]. New designs, management principles, and approaches to codes and standards should embrace this complexity. Competencies that emphasize compatibility, connectivity, and modularity of hardware to facilitate easier changing of components and information sharing should be embraced at the asset level[65]. At larger scales we should seek to implement software and cyber-technologies not simply for their efficiencies, but foremost to help make sense of the complex environments infrastructure will operate in. Increasing integration of cyber technologies into physical ones will create new security threats, interdependencies and capabilities that will add to the complexity, and will require new competencies in how they're managed[38,66], and new adaptive institutions to serve the public's interests of privacy, security, and community governance[67]. Artificial intelligence, automation, and other disruptive technologies will certainly add to the complexity, but in doing so may provide much needed guidance in sense- and decision-making processes. Infrastructure services should create conditions where ecological and social systems can support or augment what has traditionally been met exclusively by engineered technologies. Green infrastructure, biomimicry, and safe-to-fail thinking, for example, can reduce the demands placed on engineered infrastructure while introducing flexibility and augmenting the extensibility of the system in the face of surprise disturbances[10,37,68–70].

To catalyze resilience in institutions, the divisional bureaucratic forms of infrastructure governance that silo expertise and emphasize rigidity should begin transitioning to management forms that emphasize the ability to assess, create, share and utilize multiple knowledge types across multiple domains. Infrastructure governance is conventionally managed by disciplinary expertise (administratively structured as divisions with layers of middle management and a core of people who do the basic work) where problems are relegated to a particular division and leadership is responsible for making sense of changing environments[71–74]. This structure is remarkably effective when standardized work and technological control of a narrow set of variables are the goals[75,76]. However, the structure works against risk taking and innovation by creating barriers for ideas from the frontline workforce to reach upper management; division specific goals work against cross-division problem solving, and is conducive to cultural fortresses through the recruiting and promotion of workers within divisions[77]. In the Anthropocene, infrastructure agencies will need to focus on sensing and understanding changing conditions faster, and testing and evaluating strategies in increasingly uncertain environments. To do this, organizations will need to enable intellectual assets by leveraging distributed intelligence instead of relying on upper management, focusing on speed, and leading through adaptability, knowledge and learning[78]. To change, institutions will need to create conditions where roles (and identities) can be renegotiated and a critical mass of the workforce aligns their agendas with that of leadership[79]. In doing so leadership may need to make the case that the relevance of the organization will be compromised under business-as-usual operating conditions, its ability to thrive in the future will be diminished, and the well-being of workers and those who rely on services will be diminished if restructuring does not occur. In restructuring, infrastructure agencies should both empower frontline workers with the tools and knowledge to sense changing environmental conditions, and create flexible leadership models that can shift between conventional and adaptive leadership models. Whereas conventional *administrative* leadership focuses on formal managerial roles to plan and coordinate activities, *adaptive* leadership models emphasize adaptive, creative, and learning actions that emerge from interactions with complex systems[78]. Administrative leadership is appropriate for times of stable conditions, but organizations must be able to switch to adaptive models when volatility or uncertainty arises by creating hierarchies that seek change and allow for the clashing of knowledge to create new insights. These more adaptive and insight-enabling hierarchies can facilitate learning that leads to the creation of new knowledge[78].

The core competencies taught in education and training of infrastructure practitioners, whether at a university or on the job, should be restructured both in terms of content as well as the competencies needed to tackle wicked problems in complex environments. Engineering undergraduate education specifically, should adapt and reform itself with the understanding of the critical role engineers play in urban sustainability and resilience. More broadly, while disciplinary expertise will always be needed, it is not sufficient by itself, and we must arm practitioners with the tools needed to address growing complexity and the changing nature of infrastructure. The specific forms of education may not be clear, but several competencies repeatedly emerge in Anthropocene and engineered system literature that can guide how curricula change. First, we must learn to navigate complex systems and not just their artifacts, and in doing so pay far more attention to the dynamics of the systems that infrastructure affect[80]. We must relinquish the idea that we will fully understand and control the environments in which infrastructure systems deliver services. Instead, we must recognize that the systems we are deploying will be affected in ways that we could never predict[81]. Prior to designing or implementing infrastructure there needs to be a shared understanding of what the systems do. With a larger number of stakeholders (enabled say through new information flows and increasing virtual connectivity) who have differing perspectives, this may be increasingly challenging. Approaches that emphasize goal sharing, trust building, and creating joint meaning of what infrastructure should do become necessary[82]. Instead of a focus on solving a problem, infrastructure managers should be taught to use judgment and approach their systems as a process of navigation through an uncertain environment. It is the process of learning about change that becomes important, less so the solution. In doing so there should be an emphasis on experimentation, that in the process of planning and through the deployment of a short-term solution, learning about the environment will occur. Lastly, cyber competencies are necessary to ensure that as our physical systems increasingly incorporate cyber-technologies into their designs, that the vulnerability, security, and effect on services are appropriately managed.

Taken together, the restructuring of infrastructure technologies, governance, and education to build resilience capacity for the emerging challenges of the Anthropocene is a monumental but necessary undertaking. The systems that we rely on today will stay relevant for some time, but are likely to increasingly become incapable of responding to the rapidly changing conditions of the future. The transformations discussed are aligned with the adaptive and transformative capabilities central to resilience theory, and support engineered systems' ability to respond to foreseen and unforeseen conditions. Positioning resilience as a guiding framework for infrastructure is critical to ensuring that basic and critical needs are met into the future, as demands and environments change.

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M.C. led the framing and writing of the perspective. B.U., B.A., M.G., C.S., S.M., K.S., B.P., and T.M. contributed to the writing and framing of the perspective.

COMPETING INTERESTS

The authors declare no competing interests.

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