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Infrastructure and the cognitive ecosystem: an irrevocable transformation

Mikhail V Chester* and **Braden Allenby**

Metis Center for Infrastructure and Sustainable Engineering, Civil, Environmental, and Sustainable Engineering, School of Sustainable Engineering and the Built Environment, Arizona State University, 660 South College Avenue, Tempe, AZ 85287-3005, United States of America

* Author to whom any correspondence should be addressed.

E-mail: mchester@asu.edu

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Abstract

Disruption of legacy infrastructure systems by novel digital and connected technologies represents not simply the rise of cyberphysical systems as hybrid physical and digital assets but, ultimately, the integration of legacy systems into a new cognitive ecosystem. This cognitive ecosystem, an ecology of massive data flows, artificial intelligence, institutional and intellectual structures, and connected technologies, is poised to alter how humans and artificial intelligence understand and control our world. Infrastructure managers need to be ready for this paradigm shift, recognizing their systems are increasingly being absorbed into an emerging suite of data, analytical tools, and decisionmaking technologies that will fundamentally restructure how legacy systems behave and are controlled, how decisions are made, and most importantly how workers interact with the systems. Infrastructure managers must restructure their organizations and engage in cross-organizational sensemaking if they are to be capable of navigating the complexity of the cognitive ecosystem. The cognitive ecosystem is fundamentally poised to change what infrastructures are, necessitating the need for managers to take a close look at the functions and actions of their own systems. The continuing evolution of the Anthropocene and the cognitive ecosystem has profound implications for infrastructure education. A sustained commitment to change is necessary that restructures and reorients infrastructure organizations within the cognitive ecosystem, where knowledge is generated, and control of services is wielded by myriad stakeholders.

1. Introduction

Disruption of legacy infrastructure systems by novel digital and connected technologies represents not simply the rise of cyberphysical systems as hybrid physical and digital assets but, ultimately, the integration of legacy systems into a new *cognitive ecosystem*. This cognitive ecosystem, an ecology of massive data flows, artificial intelligence, and connected technologies, is poised to alter how humans and artificial intelligence understand and control our world (Smart *et al* 2017, Allenby 2021). To be prepared for this paradigm shift does not simply mean that infrastructure managers need better tools to integrate cybertechnologies and protect against new types of vulnerabilities, but that, more significantly, their systems are becoming increasingly absorbed into an emerging suite of data, analytical tools, and decisionmaking technologies that will fundamentally restructure how legacy systems behave and are controlled, how decisions are made, and most importantly what the systems fundamentally are.

Consider the rise of web mapping, such as Google Maps and Apple Maps, and the control they exert over transportation services. These services now route a significant and increasing portion of vehicle traffic. Routing is based on a cognitive overview of the system only available to the mapping providers, which provides insights into the network and its use that far exceeds the information streams available to legacy transportation agencies—from in-pavement loop detectors and traffic cameras on a limited portion of the network. Google and Apple Maps—informed by millions of mobile phone users—can see problems unfold in real time (Herrera *et al* 2010), predict traffic ahead of time using AI (Herring *et al* 2010, Lau 2020), and adjust trips to avoid the problem (Powelson and Stoltzman 2016), effectively optimizing how the system is used based on their objectives (Tseng and Ferng 2021). Objectives range from reducing travel time to reducing fuel use (Dicker 2021, Google 2023), making such mapping software one of the most powerful and least recognized environmental technologies released to the public. These mapping platforms are not simply changing how traffic moves but are more so redefining what transportation systems are, an emerging ecosystem of novel technologies controlled by novel data streams accessible to increasing numbers of stakeholders steered by algorithms, layered on and changing the dynamics of existing transportation systems (Chester and Allenby 2021a).

To reduce the integration of legacy services with the cognitive ecosystem as one of technology integration is wholly insufficient, especially since the cognitive ecosystem itself includes not just technology and data but also the cultural, institutional, and disciplinary dimensions that are an integral part of it. The rise of the cognitive ecosystem is just beginning to transform how knowledge management (creating, sharing, using, and managing knowledge in an organization, Girard and Girard 2015) and sensemaking (a shared comprehension of how to interpret the environment that is implemented through the application of tacit and explicit knowledge, Weick 1995, Cook and Brown 1999) happens in infrastructure systems and services are consumed, and how this knowledge can be used as a foundation for increasingly integrated and global systems with far greater diversity of control. The infrastructure community must accept and embrace this shift and reimagine how their organizations make sense of increasingly complex interactions with their environments and within their systems (i.e., internal and external complexity, Simon 1996).

2. Rise of the cognitive ecosystem

It is inherent in the definition of the Anthropocene that regional and planetary systems become infrastructure, and that they are integrated with traditional infrastructure in novel ways that generate significant complexity and emergent behaviors (Chester and Allenby 2021b). There is a growing consensus that we are now living in the Anthropocene, an era where humans are increasingly in control of planetary systems and human activities, and technologies are rapidly accelerating and integrating (Steffen *et al* 2015, 2016). These trends make it especially difficult to perceive fundamental shifts in global systems that might provide some insight into possible futures. Therefore, it is unsurprising that the rise of a new global ecosystem with profound implications for infrastructure systems of all kinds, including the institutional and educational structures that support them, has gone unperceived and unremarked. This ecosystem, which both permeates all infrastructure and is also a critical infrastructure in itself, is the cognitive ecosystem.

The cognitive ecosystem is an emerging and highly complex feature of an increasingly anthropogenic planet. It integrates functionality from several more traditional technologies and infrastructures from communications systems such as 5G and backbone ICT networks; to computational capabilities in everything from home devices and automobiles to vast server farms; to increasingly powerful AI tools such as generative AI; to the rules, regulations, venture capitalists, and social media systems that co-evolve with the technologies. Figure 1 illustrates the convergence of these capabilities as three domains: the data economy (data generation and distillation services), the cognitive infrastructure (institutions, technologies, services, and products that supply the cognitive components, including perception, intelligibility, and problem-solving), and the institutional and services infrastructure (institutions and platforms that support the cognitive ecosystem, including ancillary fields such as behavioral economics and neuroscience) (Allenby 2021). Within each domain, legacy physical infrastructure systems (assets that have typically been disconnected from cybertechnologies) are becoming integrated with novel digital (non-physical) systems (including sensors, communication technologies, cloud-based systems that store and analyze data, and increasingly make decisions about how the asset should operate) that expand the capabilities of the cyberphysical systems, decentralize control by increasing the number of stakeholders able to access information from the systems and affect service use, and increasingly allow AI to make decisions.

This emerging ecosystem is cognitive because it increasingly displays the functions associated with cognition at multiple scales, including perception, information processing, internal and external communication, conceptualization, learning, reasoning, problem-solving, and memory. This evolving distributed cognition system increasingly integrates several apparently unrelated infrastructures, services, institutions, and technologies tied together by technical tools such as AI and a vast array of institutional structures and networks. The important defining characteristics of the cognitive ecosystem are shown in figure 2.

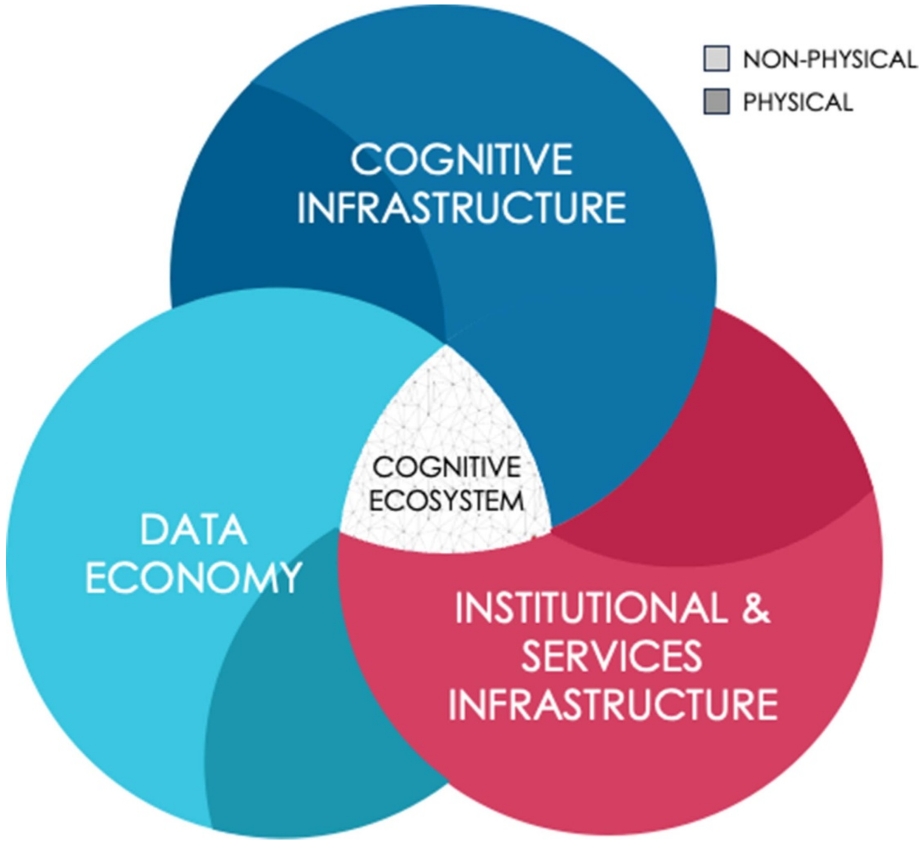

Figure 1. Three Domains of the Cognitive Ecosystem. Lighter-colored areas represent non-physical (digital) systems, and darker-colored areas physical and often legacy systems. The relative area of each circle (domain) shaded as physical or non-physical is arbitrary.

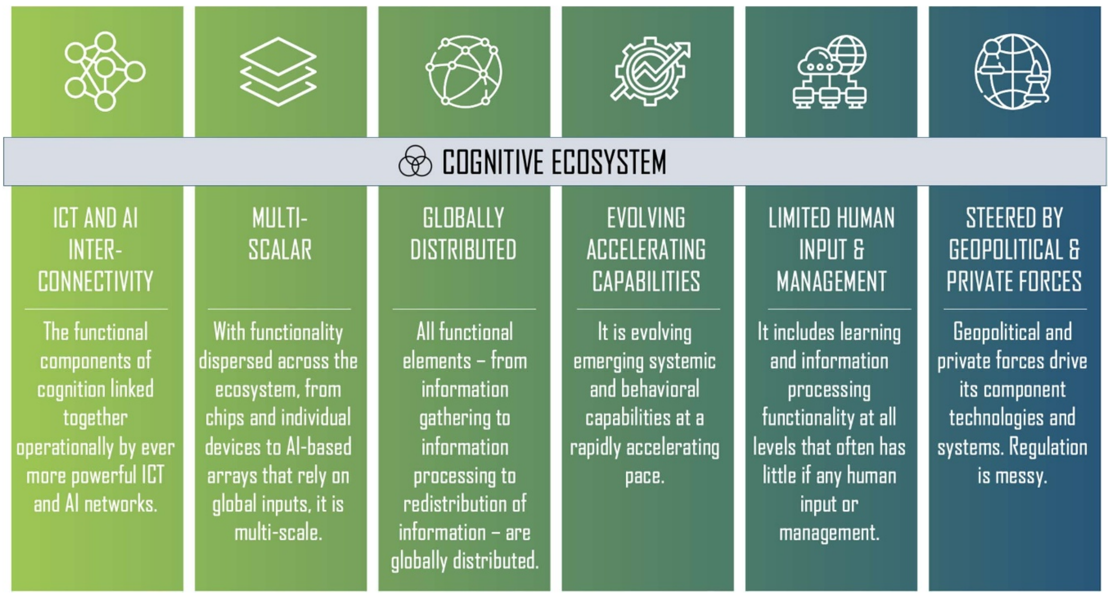

Figure 2. Characteristics of the Cognitive Ecosystem. Adapted from Allenby (2021).

3. Infrastructures as knowledge enterprises

Infrastructures—like any other human-built system—are, in many ways, first and foremost knowledge enterprises (Miller and Muñoz-Erickson 2018). While the design, management, and financing of infrastructures often focus on physical assets, their operations, and how they are managed, there are foundational processes that define how infrastructure agencies make sense of their environments (Chester *et al* 2020) and attenuate or amplify particular types of information between layers of management to make decisions (Chester and Allenby 2022). An organization (infrastructure or otherwise) is intentionally designed to take in a select stream of information about the environment (Beer 1985). The specific information taken in is an artifact of both the legacy organizational goals established at the inception of the agency (often decades ago) and how the organization has modernized in response to the perceived environment and mission change. If the organization has not felt compelled to change, that their environments are stable and their services uncompetitive, they likely maintained knowledge-making processes that reflect legacy priorities.

Remaining locked-in to legacy knowledge-making processes means that infrastructure systems are increasingly decoupled from their changing, expanding, integrating, uncertain, and increasingly complex environments. This decoupling implies that infrastructure agencies will be increasingly marginalized by the cognitive ecosystem and the introduction of a growing number of players who are able to exert control over their systems. Complexity in the context of infrastructure is both external and internal (Simon 1996). External complexity refers to rapidly changing and increasingly complex environments in which infrastructures must function—driven by climate change, uncertain financing of aging assets, the evolution of coupled technologies, and social and cultural change that affect demand. Internal complexity describes infrastructures themselves, the rapid cyber integration of digital and connected technologies that creates both new possibilities as well as vulnerabilities (Chester and Allenby 2020). Infrastructure agencies must constantly modernize their systems to engage with this complexity, adapting their systems to have a sufficient repertoire of responses relative to what the environment introduces, i.e., requisite complexity (Chester and Allenby 2022). If climate change is producing more frequent and extreme weather events, then infrastructure agencies need to design for deep uncertainty and novel resilience strategies that they would not have before. As cyber-attacks escalate, agencies will need new knowledge and new competencies to protect their systems (Chester and Allenby 2020). Failure to change how the organization takes in the knowledge of these changing conditions and makes sense of this knowledge towards appropriate action results in systems being increasingly intervened in by new players. Our need for water, energy, and mobility will not disappear anytime soon, but who controls—or deliberately disrupts—how those services are used and delivered might.

New knowledge structures are needed for infrastructure systems that recognize the increasing fuzziness of their changing system boundaries in the cognitive ecosystem. As cybertechnologies become integrated into infrastructures, there is an accelerating emergence of cross-system functionality (Chester and Allenby 2020). One infrastructure will integrate with another in novel ways, enabled by information and communication technology functionality that previously did not exist. The demand for one service can be tied to the availability of another, e.g., the spinning up and down of water treatment technologies to reduce energy demand (Murray *et al* 2018). Novel monitoring technologies are being developed for co-located underground assets (Daulat *et al* 2022). An abundance of research has emerged on managing electric vehicle charging within supply constraints and reducing emissions (Sundstrom and Binding 2012, Hoehne and Chester 2016). These functionalities represent the emergence of trans-infrastructure systems supported by a foundation of cybertechnologies with their underlying data, analytical infrastructures, and artificial intelligence decisionmaking capabilities. Infrastructures also become a critical input to the data systems that support apparently unrelated functions, therefore becoming feedstock for behaviors that may arise elsewhere but are in part shaped by infrastructure. Whereas in the past knowledge- and sensemaking could be designed for and within a single infrastructure, this no longer appears to be the case. Infrastructures are being rapidly integrated into a cognitive ecosystem.

4. Infrastructures and the cognitive ecosystem

Positioning infrastructure managers to be better capable of navigating their systems as part of the cognitive ecosystem will fundamentally require a restructuring of organization and cross-organizational sensemaking. The cognitive ecosystem is reaching a tipping point, where learning and networked technologies have accelerated to the point where legacy institutional knowledge-making paradigms are unable to keep up. This hasn't been a problem in the past because systems were largely independent, controlled by a handful of agencies, and operating in environments with greater predictability and relatively slow change cycles. A transportation agency could largely operate without great concern for the dynamics of the energy system or navigation systems routing traffic. With the growth of the cognitive ecosystem, all systems converge on interconnectedness—enabled by cyberinfrastructure layers that support data flows and analysis—and become part of much more extensive systems in terms of both connections and global scale. The legacy knowledge-making models that pervade infrastructure agencies are simply not structured to make sense of this new paradigm. The Anthropocene is creating these major global systems. Sensemaking will differ across scales. On the ground, legacy knowledge will always be needed about how to design and operate assets and subsystems (although it may be generated increasingly by artificial intelligence). However, at broader scales of both functionality and geography, new sensemaking models will be needed to recognize the changing nature and dynamics of systems and be able to more quickly recognize and negotiate roles in terms of how the systems are being steered and to what end.

The potential for accelerating cycle times within cognitive ecosystem technologies means that infrastructure agencies must root the management of their systems in principles of agility (ability to maintain function in a non-stationary future) and flexibility (ability to meet changing demands) (Chester and Allenby 2019). We refer to cycle times as the time between new generations of technologies, and in the Anthropocene, we can expect cognitive ecosystem cycle times to decrease as economies of scale are realized in data collection and information processing. Over the course of only a few months in early 2023, the world was exposed to ChatGPT, whose functionality was rapidly integrated into existing software. Within months of its release, the ChatGPT engine was quickly upgraded with greater imagination, sophisticated reasoning, multilingual proficiency, and the capacity to process visual information (Scharth 2023). Multiple competing AI systems were released, and the world was suddenly thrust into a dialogue of what these now seemingly mature and rapidly evolving technologies mean. Whether AI, integrated technologies (such as vehicle-to-grid turning cars into home energy systems), or distributed technologies (such as WiFi, rooftop solar, or mobility as a service), the implications of rapidly evolving technologies are serious for infrastructure agencies that have been structured around environments that have been slow to change and perceptions of no competition for service. The divide between how fast environments are changing and the capabilities of infrastructure organizations to respond is referred to as a *decoupling*. Accelerating organizational change starts with the structure and function of infrastructure governance, creating the capabilities to scan for future game changers (horizon or future scanning), practice horizontal governance, commit to sustained adaptation, and design for loose fit (allowing elements within the organization to restructure easily) (Chester and Allenby 2022).

Fundamentally, the cognitive ecosystem is poised to alter what infrastructures are, producing a need for managers to self-reflect on the roles and behaviors of their systems. Reflection on the changing nature of infrastructure systems is paramount to their success, and any narrative that assumes that legacy systems will persist in slightly modified forms should be viewed with skepticism. While societies may always need water, energy, mobility, shelter, and other basic services, in some manifestations, the underlying structures and functions of legacy infrastructure systems that have delivered those services appear to be about to change significantly. This change appears to be increasingly driven by new technologies (including AI) and players that are able to harness data and agile and disruptive technologies. To this end, infrastructure managers should embark on creative exercises to reimagine the roles of their services and organizations in the deep future. They should support efforts to train their workforce to be capable of navigating this new frontier.

5. Preparing infrastructure leaders

The continuing evolution of the Anthropocene and the cognitive ecosystem has profound implications for education in general and infrastructure education in particular. Engineering of infrastructures is essentially structured problem-solving that relies heavily on rational, usually quantitative, models and tools. As cognition diffuses across highly complex information structures, increasingly containing AI capability at all scales from the chip to the infrastructure component to the overall infrastructure system, and as the increasing complexity of the social, political, cultural, and economic structures become ever more tightly bound to built systems, reductionist, disciplinary frameworks which characterized the early Enlightenment approach to education fail (Allenby *et al* 2009, 2011). Modern problem-solvers, whether they rely on quantitative or qualitative analytics and methodology, must become more agile, adaptive, and sophisticated in their approaches, and the education provided to them needs to adapt to support those capabilities. The experience with generative AI, such as ChatGPT, the most rapidly adopted and diffusing technology in history, with 100 million users in the first two months, illustrates the need for a more flexible, agile, and adaptive education system. It is true that education is both inherently conservative—tenure, for example, being a good way to ensure significant inertia—and institutionally rigid, relying on such reactionary mechanisms as peer review and accreditation programs such as ABET. Nonetheless, a few obvious ideas suggest themselves. For one, given the new capabilities which technology offers by the week, it is critical to develop institutionalized mechanisms that routinely zero-base the curriculum, asking what needs to be kept, what needs to be added, and what can be dropped. This will require a degree of flexibility and imagination that the academy has yet to display. For another, every course should, directly or indirectly, embrace the implications of the cognitive ecosystem, in particular, the need for students to be able to implement and work with AI and the constant need for attention to cybersecurity issues and vulnerabilities.

6. Conclusion

By asking how organizations should be structured for the challenges of the future, organizations take a critical step to reflect on bureaucratic norms, legacy priorities, and gaps between what the organization is capable of and what it needs to do going forward (Jessop 2002, Chester *et al* 2020). However, simply reflecting is not enough. Infrastructure organizations will need to commit to sustained change that restructures and reorients the organization within a cognitive ecosystem where knowledge is generated, and control of services is wielded by myriad stakeholders. It may be that the successful infrastructure agency of the future is one that positions itself to build consensus on how services are produced and consumed (Muñoz-Erickson *et al* 2017) and away from legacy models that emphasize control over services (Chester *et al* 2023), and is in a constant state of reinvention keyed to the accelerating cycle times of relevant technologies and the cognitive ecosystem itself.

Data availability statement

No new data were created or analysed in this study.

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ORCID iD

Mikhail V Chester https://orcid.org/0000-0002-9354-2102

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