CRITICAL INFRASTRUCTURE INTERDEPENDENCIES

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Abstract

The term "infrastructure" is defined as a network of interdependent systems and processes (usually private) which work closely and convergent to produce and distribute a continuous flow of goods and services essential to the development of a nation (society). The critical infrastructures of a country are interconnected and mutually dependent in many ways, both physically and through a series of communications and information technologies. This causes the disruptions produced to the infrastructure to affect, directly or indirectly, other facilities or they may have a major impact on a relatively large geographical regions, with repercussions on the global economy.

The fact that nations’ critical infrastructures are highly interconnected and mutually dependent in complex ways, both physically and through a host of information and communications technologies (so-called “cyberbased systems”), is more than an abstract, theoretical concept. As shown by the 1998 failure of the *Galaxy 4* telecommunications satellite, the prolonged power crisis in California, and many other recent infrastructure disruptions, what happens to one infrastructure can directly and indirectly affect other infrastructures, impact large geographic regions, and send ripples throughout the national and global economy.

In the case of the Galaxy *4* failure, the loss of a single telecommunications satellite led to an outage of nearly 90% of all pagers nationwide. From an interdependency perspective, it also disrupted a variety of banking and financial services, such as credit card purchases and automated teller machine transactions, and threatened key segments of the vital human services network by disrupting communications with doctors and emergency workers. In California, electric power disruptions in early 2001 affected oil and natural gas production, refinery operations, pipeline transport of gasoline and jet fuel within California and to its neighboring states, and the movement of water from northern to central and southern regions of the state for crop irrigation. The disruptions also idled key industries, led to billions of dollars of lost productivity, and stressed the entire Western power grid, causing far-reaching security and reliability concerns.

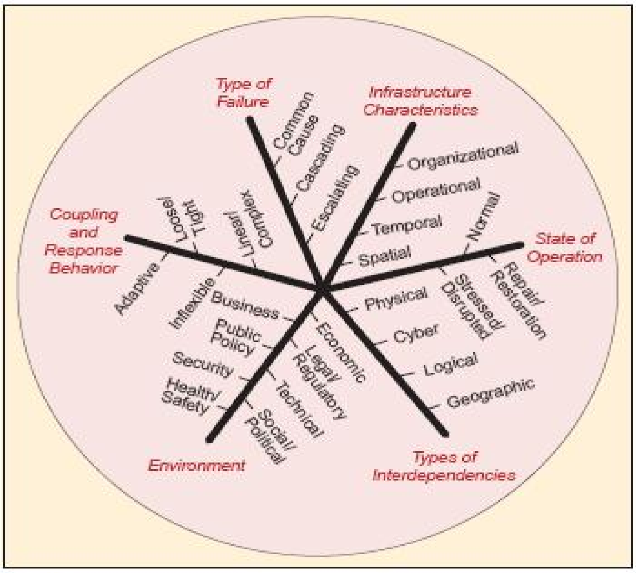

Figure 1. *Dimensions for describing infrastructure interdependencies.*

Identifying, understanding, and analyzing such interdependencies are significant challenges. These challenges are greatly magnified by the breadth and complexity of critical national infrastructures. These infrastructures, which affect all areas of daily life, include electric power, natural gas and petroleum production and distribution, telecommunications (information and communications), transportation, water supply, banking and finance, emergency and government services, agriculture, and other fundamental systems and services that are critical to the security, economic prosperity, and social well-being of the nation.

Further complicating this challenge is a broad range of interrelated factors and system conditions that we represent and describe in terms of six “dimensions,” as depicted in Fig. 1. They include the technical, economic, business, social/political, legal/regulatory, public policy, health and safety, and security concerns that affect infrastructure operations. The environment comprising these concerns influences normal system operations, emergency operations during disruptions and periods of high stress, and repair and recovery operations. The degree to which the infrastructures are coupled, or linked, strongly influences their operational characteristics. Some linkages are loose and thus relatively flexible, whereas others are tight, leaving little or no flexibility for the system to respond to changing conditions or failures that can exacerbate problems or cascade from one infrastructure to another.

These linkages can be physical, cyber, related to geographic location, or logical in nature. Interdependent infrastructures also display a wide range of spatial, temporal, operational, and organizational characteristics, which can affect their ability to adapt to changing system conditions. And finally, interdependencies and the resultant infrastructure topologies can create subtle interactions and feedback mechanisms that often lead to unintended behaviors and consequences during disruptions.

We use this framework, namely, the dimensions shown in Fig. 1, to explore the challenges and complexities of interdependency. We set the stage for this discussion by explicitly defining the terms *infrastructure*, *infrastructure* *dependencies*, and *infrastructure interdependencies* and introducing the fundamental concept of infrastructures as complex adaptive systems.

Concepts and Definitions

Infrastructure

The term *infrastructure* is defined as "the underlying foundation or basic framework (as of a system or organization)". In a report from 1997, addressed to the U.S. President, an infrastructure is defined as a network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services.

In its deliberations, the report narrowly focused on eight critical infrastructures "whose incapacity or destruction would have a debilitating impact on defense and economic security". These eight are telecommunications, electric power systems, natural gas and oil, banking and finance, transportation, water supply systems, government services, and emergency services. In a broader perspective, other examples of infrastructures (in addition to the report's eight critical infrastructures) include food/agriculture (production, storage, and distribution), space, numerous commodities (iron and steel, aluminum, finished goods, etc.), the health care industry, and the educational system.

Infrastructures as Complex Adaptive Systems

All of the aforementioned critical infrastructures have one property in common—they are all complex collections of interacting components in which change often occurs as a result of learning processes; that is, they are complex adaptive systems (CASs). Seen from this perspective, which has important benefits for modeling and analysis, each component of an infrastructure constitutes a small part of the intricate web that forms the overall infrastructure.

All components are influenced by past experiences. For example, electric transformers slowly degrade from overuse, and natural gas pipes age over time. And many components are individually capable of learning from past experiences and adapting to future expectations, such as operating personnel who try to improve their performance and real-time computer systems that adjust electric generator outputs to meet varying power loads.

From a CAS perspective, infrastructures are more than just an aggregation of their components. Typically, as large sets of components are brought together and interact with one another, synergies emerge. Consider the emergence of reliable electric power delivery from a collection of well placed electric generators, transformers, transmission lines, and related components. Simply aggregating the components in an ad hoc fashion will not ensure reliable electricity supplies. Only the careful creation of an intricate set of services will yield a system that reliably and continuously supplies electricity. This additional complexity exhibited by a system as a whole, beyond the simple sum of its parts, is called emergent behavior and is a hallmark of CASs.

Complex adaptive systems do not require strong central control for emergent behaviors to arise. In fact, many CASs would not function as well with such restrictive operating procedures. However, it is vital for managers responsible for systems of this type, such as the eight critical infrastructures defined by the report, to recognize the nature—and particularly the emergent behaviors—of their systems.

One effective way to investigate CASs is to view them as populations of interacting agents. An agent is an entity with a location, capabilities, and memory. Although the term *agent* is frequently used when discussing specific modeling techniques, we use it here in the abstract to describe entities with general characteristics.

The entity’s location defines where it is in a physical space, such as a geographic region, or an abstract space, such as the Internet, or both. The entity’s capabilities define what it can do from its location, such as an electric generator increasing its output or an oil pipeline reducing its pumping rate. The entity’s memory defines what it has experienced, such as overuse or aging. Memory is often expressed in the form of agent state variables. Most infrastructure components have a location and capabilities and are influenced by past experiences. Thus, most infrastructure components can be viewed as agents.

Consider an oil pipeline. The pipeline’s location can be expressed physically as a set of latitudes and longitudes and abstractly as a specific stage in the oil delivery process. The capabilities of the pipeline include not only its ability to move oil, but also the ways in which it responds to emergencies. Naturally, these responses may not always be positive.

For instance, the pipeline might respond to a rupture or the loss of electricity at a pumping station by simply shutting down the flow of oil. The memory of the pipeline may include the current and past flow rates, pressures, temperatures, operating status of its pumps, and so forth.

Agents communicate with one another as they operate in a particular environment. Each agent receives inputs from other agents and sends outputs to them. These “inputs” and “outputs” need not be resources used in, or products made by, an infrastructure or process. Metrics that describe the state of an agent can also be viewed as outputs that other agents can sense (use as input) and act upon. The inputs to an oil pipeline include electricity to power the pumps and the current demand for oil, whereas its outputs include the flow of oil to external agents and price information.

Dependency

Consider a specific, individual connection between two infrastructures, such as the electricity used to power a telecommunications switch. In this case, the relationship is usually unidirectional; that is, infrastructure *i* depends on *j* through the link, but *j* does not depend on *i* through the same link:

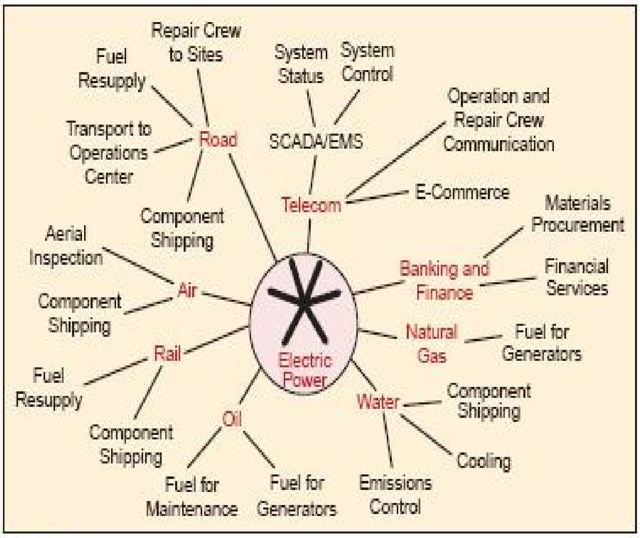

Figure 2. *Examples of electric power infrastructure dependencies.*

Dependency: A linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other.

Fig. 2 illustrates the concept. Under normal operating conditions, the electric power infrastructure requires natural gas and petroleum fuels for its generators, road and rail transportation and pipelines to supply fuels to the generators, air transportation for aerial inspection of transmission lines, water for cooling and emissions control, banking and finance for fuel purchases and other financial services, and telecommunications for e-commerce and for monitoring system status and system control (i.e., supervisory control and data acquisition (SCADA) systems and energy management systems (EMSs)). During emergencies or after component failures, the electric power infrastructure will have potentially different yet critical dependencies on the same infrastructures. For example, the utility may require petroleum fuels for its emergency vehicles and emergency generators and road transportation (and in some cases rail and air transportation) to dispatch repair crews and replacement components.

As depicted in Fig. 2, electric power is the *supported* infrastructure, and natural gas, oil, transportation, telecommunications, water, and banking and finance are *supporting* infrastructures. Although not shown, emergency and government services are also supporting infrastructures.

Interdependency

When examining the more general case of multiple infrastructures connected as a "system of systems," we must consider interdependencies. Infrastructures are frequently connected at multiple points through a wide variety of mechanisms, such that a bidirectional relationship exists between the states of any given pair of infrastructures; that is, infrastructure *i* depends on *j* through some links, and *j* likewise depends on *i* through other links:

Interdependency: A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each is dependent on the other.

The term *interdependencies* is conceptually simple; it means the connections among agents in different infrastructures in a general system of systems. In practice, however, interdependencies among infrastructures dramatically increase the overall complexity of the "system of systems."

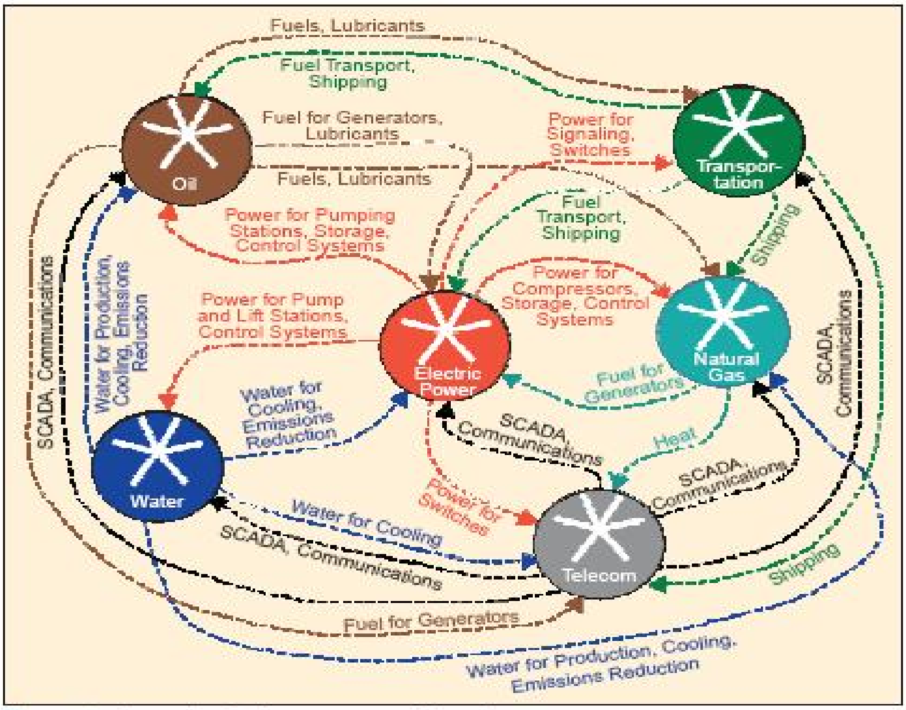

Figure 3. *Examples of infrastructure interdependencies.*

Fig. 3 illustrates the interdependent relationship among several infrastructures. These complex relationships are characterized by multiple connections among infrastructures, feedback and feedforward paths, and intricate, branching topologies. The connections create an intricate web that, depending on the characteristics of its linkages, can transmit shocks throughout broad swaths of an economy and across multiple infrastructures. It is clearly impossible to adequately analyze or understand the behavior of a given infrastructure in isolation from the environment or other infrastructures. Rather, we must consider multiple interconnected infrastructures and their interdependencies in a holistic manner. For this reason, we use the term *interdependencies* rather than *dependency* throughout the remainder of this article.

Dimensions of Infrastructure

Interdependencies

Using these concepts and definitions, we now explore the six dimensions shown in Fig. 1. These dimensions and their components are descriptive and are intended to facilitate the identification, understanding, and analysis of interdependencies. They do not represent a comprehensive set of orthogonal interdependency metrics, although they provide a foundation for developing such metrics.

Types of Interdependencies

Interdependencies vary widely, and each has its own characteristics and effects on infrastructure agents. In the sections that follow, we define and examine in detail four principal classes of interdependencies: physical, cyber, geographic, and logical. Although each has distinct characteristics, these classes of interdependencies are not mutually exclusive.

Physical Interdependency

Two infrastructures are physically interdependent if the state of each is dependent on the material output(s) of the other. As its name implies, a physical interdependency arises from a physical linkage between the inputs and outputs of two agents: a commodity produced or modified by one infrastructure (an output) is required by another infrastructure for it to operate (an input). In this manner, perturbations in one infrastructure can ripple over to other infrastructures. Consequently, the risk of failure or deviation from normal operating conditions in one infrastructure can be a function of risk in a second infrastructure if the two are interdependent.

Cyber Interdependency

An infrastructure has a cyber interdependency if its state depends on information transmitted through the information infrastructure. Cyber interdependencies are relatively new and a result of the pervasive computerization and automation of infrastructures over the last several decades. To a large degree, the reliable operation of modern infrastructures depends on computerized control systems, from SCADA systems that control electric power grids to computerized systems that manage the flow of railcars and goods in the rail industry. In these cases, the infrastructures require information transmitted and delivered by the information infrastructure. Consequently, the states of these infrastructures depend on outputs of the information infrastructure. Cyber interdependencies connect infrastructures to one another via electronic, informational links; the outputs of the information infrastructure are inputs to the other infrastructure, and the "commodity" passed between the infrastructures is information.

Geographic Interdependency

Infrastructures are geographically interdependent if a local environmental event can create state changes in all of them.

A geographic interdependency occurs when elements of multiple infrastructures are in close spatial proximity. Given this proximity, events such as an explosion or fire could create correlated disturbances or changes in these geographically interdependent infrastructures. Such correlated changes are not due to physical or cyber connections between infrastructures; rather, they arise from the influence the event exerts on all the infrastructures simultaneously. Note that more than two infrastructures can be geographically interdependent based on their physical proximity.

Implicit in our discussion is the fact that some interdependencies and their effects on infrastructure operations are caused by physical phenomena, whereas others result from human intervention and decisions. For example, if an electric power utility should fail, then the backup generators at a telecommunications switch start automatically, the result of physical interactions and phenomena without human intervention.

Logical Interdependency

Two infrastructures are logically interdependent if the state of each depends on the state of the other via a mechanism that is not a physical, cyber, or geographic connection.

Logical interdependencies may be more closely likened to a control schema that links an agent in one infrastructure to an agent in another infrastructure without any direct physical, cyber, or geographic connection. Consider the power crisis that emerged in California in late 2000 and the logical interdependency between the electric power and financial infrastructures.

The genesis of this crisis can be traced to the deregulation legislation that was passed in 1996 to open California's electricity market to competition. Under that legislation, California's investor-owned utilities were required to sell off their power-generating assets and purchase electricity on the open market. At the same time, however, the state experienced substantial load growth, a lack of investment in new generating capacity and transmission lines, reduced generation from aging power plants, high natural gas prices, transmission and environmental constraints, a drought in the Pacific Northwest, and a volatile spot market.

This confluence of factors, plus the fact that utilities were not permitted to pass soaring wholesale power prices through to consumers, led to an unprecedented financial crisis that pushed one of the state's largest utilities to bankruptcy and another to the brink of bankruptcy. In addition to enormous financial losses, the bond ratings of these utilities were downgraded to below investment grade (or into the status of junk bonds).

This state variable of the financial market made it nearly impossible, without intervention by the national governments, for the utilities to buy power. As a result, the utilities' abilities to provide sufficient electric power (electrical state variable) in California were decreased by their bond ratings (financial state variable), and their bond ratings were affected by their inability to produce enough power. In this example, the logical interdependency is bidirectional and does not depend on any physical or cyber connection between the electric power and financial infrastructures.

Furthermore, human decisions may play the predominant role in logical interdependencies in particular. In the previous example, the decline in financial standing of the power companies was due to human decisions. Another example is that summer vacationers may flock to the highways when gasoline prices are low, resulting in increased traffic congestion. In this case, the logical interdependency between the petroleum and transportation infrastructures is due to human decisions and actions and is not the result of a physical process.

Coupling and Response Behavior

We now examine the characteristics of the couplings among infrastructures and their effects on infrastructure responses to perturbations. The primary coupling characteristics are the degree of coupling (tightness or looseness), the coupling order, and the linearity or complexity of the interactions. The coupling characteristics and nature of the interacting agents in turn directly influence whether the infrastructures are adaptive or inflexible when perturbed or stressed.

We first classify linkages as either *tight* or *loose* depending on the relative degree of coupling. Tight coupling refers to agents or infrastructures that are highly dependent on one another. Disturbances in one agent can be closely correlated to those in another agent to which it is tightly coupled.

Disturbances tend to propagate rapidly through and across tightly coupled infrastructures. Tight coupling is characterized by time-dependent processes that have little “give” or slack. A natural-gas-fired electrical generator and the gas supply pipeline form a tightly coupled pair. In particular, if the gas-fired generator has no local gas storage and cannot switch to an alternative fuel, the generator is very tightly coupled to the gas pipeline.

Disturbances in the gas supply will have almost immediate effects on electrical generation. Loose coupling, on the other hand, implies that the infrastructures or agents are relatively independent of each other, and the state of one is only weakly correlated to or independent of the state of the other. Slack exists in the system, and the processes are not nearly as time dependent as in a tightly coupled system. For example, a coal-fired electrical generator and the diesel-powered railroad network that supplies its coal are weakly coupled. Coal-fired generators often have two or three months' supply of coal stored locally (although financial pressures are significantly reducing traditional levels of storage).

Short-term disturbances in the rail supply system rarely affect power generation, so the state of the electrical grid is thus weakly correlated to the state of the railroad through this specific interdependency. In sum, tight and loose coupling refer to the relative degree of dependencies among the infrastructures.

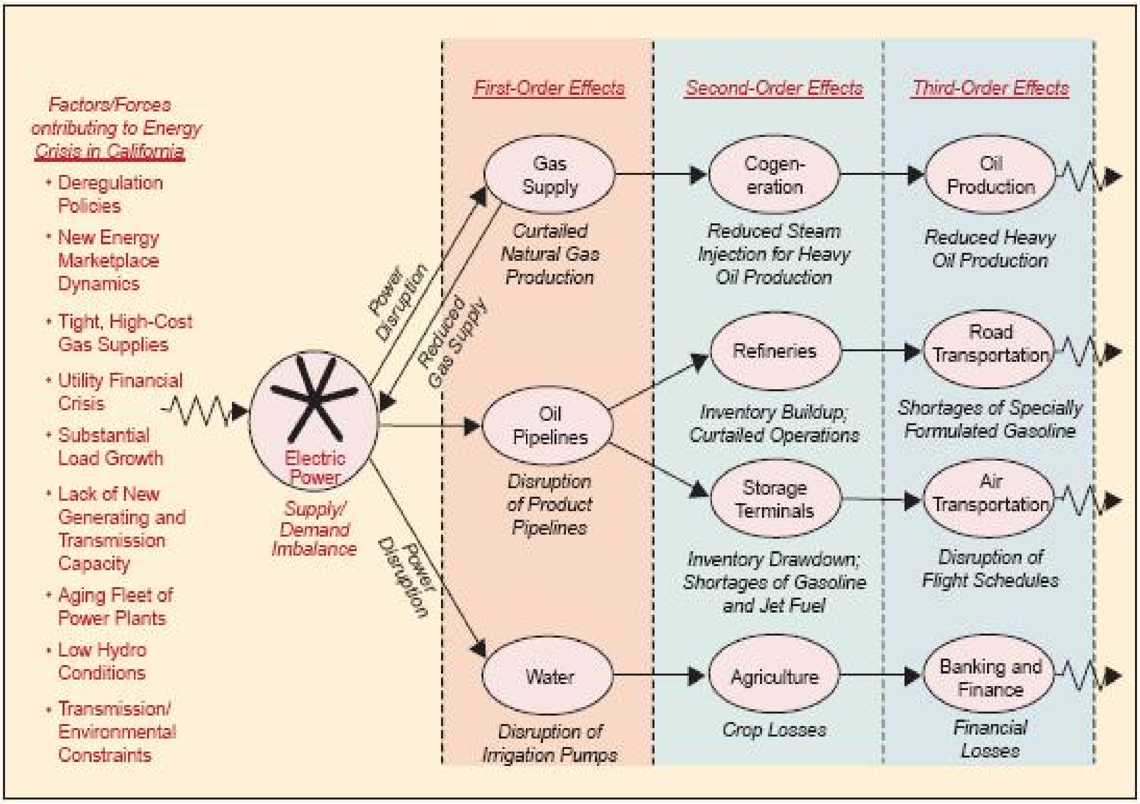

Figure 4. *Examples of nth-order interdependencies and effects.*

The *coupling order* indicates whether two infrastructures are directly connected to one another or indirectly coupled through one or more intervening infrastructures. Consider infrastructures *i, j,* and *k,* where *i* is linked to *j*, which in turn is connected to *k*, but *k* is not directly linked to *i*.

Depending on the nature of the infrastructures and their interdependencies, changes in State*i* may drive changes in State*j,* which in turn affect State*k*. These indirect linkages and state changes are commonly referred to as *n*th-order interdependencies and *n*th-order effects, respectively, where *n* is the number of linkages.

Of particular note is that feedback loops can also exist through *n*th-order interdependencies. If, for example, infrastructure *i* is coupled to *j*, *j* is coupled to *k*, and *k* is coupled through another route to *i*, then a feedback loop exists through the chain $i - j - k - \cdots - i$.

The interactions among infrastructures can be further classified as either linear or complex, as follows:

Linear interactions are those in expected and familiar production or maintenance sequence, and those that are quite visible even if unplanned.

Complex interactions are those of unfamiliar sequences, or unplanned and unexpected sequences, and either not visible or not immediately comprehensible.

Linear interactions are generally those intended by design, with few unintended or unfamiliar feedback loops. Complex interactions are likely to exist when agents can interact with other agents outside the normal production or operational sequence, whether by design or inadvertently. Such interactions can occur in systems with branching paths, feedback loops, and jumps from one linear sequence of operations to another (possibly due to geographic interdependencies). Complex interactions are generally those not intended by design, and they can be subtle and difficult to detect.

A given infrastructure can contain numerous linear and complex interactions. When examining a given interaction, however, context becomes important. Consider a natural gas pipeline. When examined in isolation from other infrastructures and the environment, the flow of gas in the pipeline may appear to be a linear process with predominantly linear interactions: gas flows from some source, traverses a gas conditioning plant, passes through many compressor stations and gateways, and finally arrives at the consumer's location.

However, in a broader context that includes couplings to other infrastructures and the environment, this apparently linear process can be complex. If, for instance, the electrical grid uses natural gas supplied by the pipeline as fuel and in turn produces electricity that powers the gas conditioning plants and compressor stations, then the coupled pipeline electrical grid system behaves more as a complex set of interactions than as two isolated, linear infrastructures. The more intricate and diverse the interconnections among agents in the infrastructures, the more complex the interactions become.

Many analyses of individual infrastructures proceed in a linear fashion, however. Analyses often make the crucial assumption that *supporting* infrastructures will continue to provide an uninterrupted supply of their goods and services, regardless of any disturbance in the *supported* infrastructure.

This assumption effectively decouples the supported infrastructure from its supporting infrastructures and focuses on the dependencies rather than on the interdependencies of the infrastructure in question. This simplistic approach may be valid for some analyses, but it overlooks the true complex nature of interconnected infrastructures. As such, it may lead to incorrect and potentially disastrous results. A clear understanding of context is thus vital in analyzing the couplings among infrastructures.

Finally, the characteristics of the agents comprising the infrastructures and their interdependencies influence whether a given infrastructure is adaptive or inflexible when stressed or perturbed. We previously noted that the hallmark of a CAS is its ability to learn from past experiences and adapt to future expectations.

Numerous factors contribute to adaptability, including the availability and number of substitutes for critical processes or products, workarounds and contingency plans, backup systems, training and educational programs for operational personnel, and even human ingenuity in the face of disasters.

Other factors may render infrastructures inflexible, such as restrictive legal and regulatory regimes, health and safety standards, social concerns, organizational policies, fixed network topologies, and the high cost of providing extensive backups and workarounds. A collection of flexible agents is more likely to respond well to disturbances and continue to provide essential goods and services than is an inflexible, rigid system that is incapable of learning from past experiences.

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