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Ibrahim, Sherwat E., Miguel A. Centeno, Thayer S. Patterson, and Peter W. Callahan. 2021. “Resilience in Global Value Chains: A Systemic Risk Approach.” *Global Perspectives* 2 (1). https://doi.org/10.1525/gp.2021.27658.

Global Epistemologies: Concepts, Methodologies, and Data Systems

Resilience in Global Value Chains: A Systemic Risk Approach

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Keywords: global value chains (gvc), systems thinking, systemic risk, global systemic risk, complexity, complex adaptive systems (cas)

https://doi.org/10.1525/gp.2021.27658

Global Perspectives

Vol. 2, Issue 1, 2021

Global value chains (GVCs) have increased efficiencies, accelerated production, reduced costs, and increased wealth and opportunities for workers, firms, nations, and the global economy as a whole. However, the benefits and efficiencies provided by these GVCs come at the cost of increasing risks. This is largely because the emergence and evolution of GVCs have been enabled by advancements in globalization, complexity, and technology, as well as the development of critical global systems that underpin these industries—such as communication, transportation, financial systems, and others. GVCs are thus only as stable as these underlying global systems upon which they depend, and are vulnerable to potential shocks to these systems.

The COVID-19 pandemic and other recent global interruptions in GVCs have demonstrated the importance of applying a systems theory approach, which allows us to identify—and eventually begin managing for—the multidimensional risks that these global industries face. Studying the stability and reliability of these global industries requires not only an understanding of risks within just the GVCs but also an awareness of vulnerabilities in numerous critical underlying systems that form the infrastructure of GVCs and the global economy. As examples, we examine six such underlying systems: health care and public health, supply chain and logistics, technology and cyber, finance, sociopolitical, and the environment. Each of these examples illustrates that disruptions, fragilities, or failures in critical underlying systems can dramatically impact GVCs as a whole and make the geographic regions in which these systems are vulnerable less attractive to industry investment and expansion.

Introducing methodologies and concepts from systems theory, we illustrate that these underlying global systems that expose GVCs to vulnerabilities are complex adaptive systems (CAS). As systems of systems composed of CAS, these GVCs consequently also can be modeled as CAS. We argue that not only does this CAS perspective help to mitigate the multilayered GVC risks through better understanding and the application of CAS tools like “adaptive management, but it also empowers policymakers to better attract GVCs to their borders by prioritizing the creation of more resilient underlying systems.

INTRODUCTION

Global value chains (GVCs) have emerged in recent decades as a framework for characterizing and examining the systemic structures of global industries. Since the GVC conceptualization was introduced in the 1990s, it has served not only as a descriptive model of the globalization of industries but also as a prescriptive paradigm to advance global economic development. GVCs are not explicitly designed, created, or orchestrated but are self-organizing systems that emerge through the aggregation of decisions by companies, industry groups, and nations pursuing self-interest (Kano 2018; Kano, Tsang, and Yeung 2020). The ability of countries to prosper has been associated with their participation in the global economy and their role in GVCs, which consider the generation and transfer of value worldwide. Developing nations are able to use the GVC perspective and structural framework to strategically attract these industries and subsequently “upgrade : advance within the industry, attain higher skill and education within the global labor force, and produce greater economic value (Ponte and Ewert 2009; Gereffi 2010; Barrientos, Gereffi, and Rossi 2011).

Recent developments of lower barriers to trade and investment, increased global access to capital, falling transportation costs, and advancements in information and com-

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munication technologies have made transnational enterprise possible, leading many critical industries to become structured as GVCs to remain competitive in an increasingly globalized world. As corporations explore global opportunities for sourcing inputs and marketing outputs, their industries broaden in geographic scope and integration to form a GVC. While generating greater efficiencies through this process of globalization, this scope and integration have also created risks.

As industries grow across borders, oceans, and continents, they become increasingly reliant upon a complex web of underlying systems over which they have minimal control—such as communication, transportation, financial systems, and others. Not only are all these far-flung critical systems impossible to fully secure around the world, but increasing global integration allows shocks, which might have once been isolated to one sector or region, to now propagate quickly through these tightly coupled underlying systems that form the architecture of GVCs. GVC stability is dependent upon the maintenance and resilience of these critical underlying systems as disruptions now have the potential to create widespread failure or collapse. Risks to these underlying systems become GVC risks, and their security is critical to the maintenance, resilience, and sustainability of GVCs as a whole.

In this article, we apply concepts from systems theory to illustrate that the underlying systems upon which GVCs depend can be best described as complex adaptive systems (CAS). We argue that as systems of systems, which are built and rely upon these underlying CAS, GVCs are CAS as well. We show that this systems theory perspective is useful in that it allows for better understanding and management of the emergent and nonlinear risks that this web of systems faces. Recent GVC disruptions due to the COVID-19 pandemic and other global shocks emphasize the importance and timeliness of this approach.

Through tools like adaptive management, which this perspective affords, GVCs can be positioned to be more nimble in the face of uncertainty, thereby increasing their resilience and stability. Finally, this perspective makes clear the importance of underlying CAS resilience for overall GVC stability. Nations seeking to take part in—or upgrade their position within—a GVC can use this perspective to prioritize underlying system development. This systems theory perspective illustrates that by emphasizing the resilience and security of the critical CAS upon which GVCs rely, nations will be able to more effectively attract investment from global industry.

We begin by outlining the conceptual framework of GVCs as a method for analyzing the structure and dynamics of global industries. As GVCs are CAS, we then outline the relevant terms and methodologies from systems theory that can provide insights into the analysis of their systemic risks. Finally, we consider how GVCs are interconnected with, and rely upon, critical underlying global systems and are thereby affected by systemic risks beyond their control. As examples, we look at six such systems—health care and public health, supply chain and logistics, technology and cyber, finance, sociopolitical, and the environment—that are each part of a larger global system of systems upon which sectors of the global economy ultimately depend. By examining each of these systems in turn, and seeing the vulnerabilities they can introduce into GVCs, we illustrate that critical risks facing GVCs are systemic in nature and require a systems approach to effectively identify and mitigate. With the introduction of this systemic risk perspective, we hope to (1) draw attention to multilayered vulnerabilities that have previously been ignored, (2) encourage management and governance strategies that increase the overall resilience of GVCs, and (3) ultimately make it easier for developing nations to recognize inroads for taking part in the value-adding activities of GVCs.

GLOBAL VALUE CHAINS (GVCS)

GVCS BACKGROUND

A GVC is the structural representation of a globalized industry, from raw materials to the end consumers. This framework or paradigm of an industry is a form of representation and analysis that begins by describing and diagramming the different processes along the chain in which value is created. Importantly, it notes where these activities are located geographically and how much value is added by the various processes as the product or service moves from the upstream end of product origination to the downstream end where the customer takes delivery. It then allows companies participating at various levels along that chain to visualize where they fall within the structure. Additionally, it enables an understanding of the governance of a global industry by depicting the connections and couplings in this chain and the loci of power and control. Analysis of GVC governance reveals the strategic leadership dynamics that influence decisions and transactions—who along that chain makes key decisions, considers outsourcing and offshoring options, sets standards and practices, has pricing power, dictates the speed of innovation, et cetera (Nadvi 2008).

A GVC is distinct from a global supply chain in that it is composed of all the companies within that industry, while a global supply chain typically includes the global activities of one single company, or the iterative sequence of inputs and distinct operations required to produce a single product (Ibrahim 2019; Carter et al. 2014). GVCs emerged as a result of industries relocating their various production processes across borders, transforming sectors from fully integrated, wholly owned, and locally contained within the borders of a single nation into dis-integrated and internationally outsourced activities. Firms source parts, components, and services from producers in several countries and, in turn, sell their outputs to firms and consumers worldwide (Antràs 2015). Today, for example, within the smartphone industry, phones may be designed in the United States; manufactured using sophisticated inputs produced in the Republic of Korea or Chinese Taipei, with final assembly carried out in China; then marketed, sold, and serviced in Europe or back in the United States.

While most of these decisions to restructure and relocate production are made one at a time by the management of individual companies in a particular industry based on improving efficiency or profitability, many of these micro choices in aggregate generate transformative macro trends in that global industry. In this sense, the governance structure of a GVC emerges in large part through this self-organizing behavior in response to opportunities and incentives for greater profitability. In the past, this emergence has been driven more by the "invisible hand of global markets and by benefits of globalization than by industrial planning or policy-making (Nakamura 2000). However, the introduction of the GVC framework has allowed corporate executives, industry groups, and policymakers to analyze, anticipate, and capitalize upon these resulting broader trends that are changing the shape and dynamics of entire industries—and with them, economic globalization.

GVC governance structures vary in their level of concentration or diffusion of power, control, and flows of capital and critical inputs. On one end of the spectrum, the GVC can be diversified, with many suppliers and many producers, trading through markets. At the other end of the spectrum, the governance structure is hierarchical, with dominant industry producers dictating terms to their suppliers. In between on this spectrum are variations of networks of buyers and their suppliers (Gereffi 2019; Gereffi and Korzeniewicz 1994; Sturgeon and Lee 2001; Humphrey and Schmitz 2000).

APPLICATIONS OF GVCS TO COMPETITIVENESS AND ECONOMIC DEVELOPMENT

GVCs have become essential for economic development and job creation in the global economy, where competition remains intense, and production is fragmented and geographically dispersed (Cattaneo, Gereffi, and Staritz 2010). Intermediate goods and services traded within GVCs account for more than 50 percent of the world s trade (United Nations Conference on Trade and Development 2013). The unbundling of world production (Baldwin 2016) into geographically fragmented activities has been historically associated in the economic literature with concepts such as multistage production (Dixit and Grossman 1982); global production sharing (Yeats 1999); vertical specialization (Hummels, Rapoport, and Yi 1998); global commodity chains (Gereffi 1999); international fragmentation (R. W. Jones and Kierzkowski 2005); subcontracting, offshoring, and outsourcing (Williamson 2008); and trade in tasks (Grossman and Rossi-Hansberg 2008). Literature studying GVCs has aimed to capture determinants of the organization of global industries by incorporating elements from industrial organization, international business, and trade and competitiveness (Porter 1986, 1990; Sölvell 2015). GVCs are politically salient and can strongly influence public sentiment and hence attitudes toward trade, trade agreements, and indeed fairness (Dollar et al. 2017).

These complex global production arrangements—enabling trade among multiple participants, each with numerous cross-border flows—have transformed the nature of global trade. When measured in terms of value-added rather than gross flows of exports and imports, this global trade today looks radically different from the past, as developing nations have focused on upgrading their production capabilities in order to contribute more high value-added processes (Dollar et al. 2017). Changes in production, participation, and trade have been extensively studied over the past three decades to highlight the increasing importance of GVCs as an imperative framework of analysis in today s economies and societies. Efforts to study the evolving architecture of GVCs and refine trade data to understand the complex value-added structure of trade in goods and services have been led by the World Bank, the Organisation for Economic Co-operation and Development (OECD), the World Trade Organization (WTO), and a number of other institutions (World Bank 2020).

The industrial linkages diagrammed through GVC analysis provide a detailed picture of the network structure and connectivity of the global economy. International trade economists can study GVC-level data on bilateral international trade flows to disentangle the intermediate inputs from the value added at each step in the chain. This type of analysis involves both empirical methods and theoretical models and reveals the changing nature of international trade. These studies use indexes from global input-output tables to identify GVC characteristics such as the production length index (measure of the average number of production stages and complexity of the value chain), the participation index (measure of the intensity of a country-sector s engagement in GVCs, as shown by the share of each export dollar that passed through a GVC), and the position index (relative measure of the location of a country-sector pair on a GVC) (L. Jones, Demirkaya, and Bethmann 2019).

Adding to these established perspectives of GVC analysis, we emphasize the criticality of underlying systems upon which GVCs are constructed and depend—such as communication, transportation, financial systems, and others—which themselves are complex global networks. Industries have moved from a model of vertically integrated localized firms to coordination among complex networks of interconnected globally dispersed actors (Gereffi, Humphrey, and Sturgeon 2005), resulting in a reliance upon critical underlying systems over which they have limited control. As the systems have grown more complex and interdependent, the risks for systemic failure have increased, as exemplified by the COVID-19 pandemic. In this way, we argue that promoting greater robustness and resilience of GVCs relies on insights of systems theory. We look at the underlying systems—and the GVCs themselves—through the lens of systems theory and global systemic risk, with the ultimate goal of better understanding, maintaining, and attracting GVCs to increase competitiveness and facilitate economic development.

SYSTEMS THEORY AND GLOBAL SYSTEMIC RISK

Recognizing that GVCs are systems-of-systems, a better understanding of critical concepts and methodologies from the fields of systems theory and global systemic risk can provide a framework for our study of GVCs. Network theory and the mathematics of graph theory allow us to diagram and model the pairwise relationships between actors—depicted as nodes—in a network diagram. The traditional approach has been to focus on the individual actors—their qualities, characteristics, agency, and behavior—in order to judge how reliably they will interact with those with whom they are connected. However, this traditional microprudential approach does not account for the complexity, interconnectedness, technological advancement, and speed inherent in our modern systems (Freixas, Laeven, and Peydro 2015).

Within systems theory, the nonlinear and unpredictable dynamics of the interactions between nodes has given rise to the field of complex adaptive systems, which recognizes that the actors respond—or adapt—to the rapidly changing dynamics of a system, giving the system a collective self-organizing behavior that cannot be anticipated or foreseen (Miller and Page 2007). Understanding of these CAS is provided by a multidisciplinary approach, combining insights from mathematics, physical sciences, and the social sciences. Study of CAS recognizes that these systems have "emergent properties—where the system dynamics cannot be explained solely by the qualities of the individual components, but instead by the complex interactions between these nodes (Corning 2002). This phenomenon of "emergence occurs when structural and behavioral changes arise from unexpected interactions between network actors that alter the fundamental structure, dynamics, and integrity of the system (Holland 1992; Barabási and Frangos 2002).

The structures of these CAS often self-organize around critical nodes, which act as hubs linking modules, collections, or subnetworks of smaller nodes to the larger network (Birdsey, Szabo, and Falkner 2017). The criticality of these hubs to the functioning of such "scale-free networks can lead to rapid nonlinear changes in the dynamics of the system, as shocks can rapidly cascade through these hub nodes and spread contagion throughout (Barabási and Albert 1999). If tipping points are reached, this cascading spread of contagion can lead to a phase change or critical transition in the functionality of the system (Holling 2001). System actors who study not just the nodes but also the structure and dynamics of linkages in these networks are better positioned to avoid such fragilities by constructing redundancies, fault tolerance, feedback loops, and other characteristics that can make network viability more robust—strong enough in the face of shocks to prevent systemic failure or the loss of the system s primary function and "identity (Walker et al. 2004; Andrachuk and Armitage 2015). Similar foresight, planning, and precautions can make actors within the network more resilient—enabling a rapid recovery—in the event of a systemic collapse (Centeno et al. 2015; Guillen 2016).

A critical insight of CAS and their emergent properties is that managing the risk of each node independently is not enough. Even if risk managers follow the standard paradigm for fiduciary governance within a network and vigilantly look outward for potential exogenous threats to their respective nodes and to the system as a whole, they often overlook endogenous failures that can manifest on their own within the system. Absent any malicious action or intent, and without any external stimulus, these endogenous threats and fragilities can prove devastating. Further, increasing interdependencies among and between underlying systems have created systems of systems where different functional domains are arrayed in multilayer networks, which all operate in concert. One such example is the global credit card system that depends on many related systems to function: the financial system, the supplier and consumer networks, the internet, the telecommunications network, and the electricity grid. A failure in any one of these underlying systems would disrupt the credit card system, sending cascading failures through the overarching economic and financial systems.

The countless variables in these CAS, the interaction effects, and the speed of propagation of information and shocks through the system require vigilant systemic awareness by its participants. As shocks cascade through these systems, they may take down not only fragile nodes but also the most prudently managed nodes within the network graph; even cautious members are susceptible to failure simply because of their participation in the complex system of systems (Centeno et al. 2015).

Scholars in ecology and conservation advocate for the iterative decision-making process of "adaptive management for dealing with the complexity, uncertainty, and constantly evolving dynamics inherent in CAS (Frieden 2010) . In contrast to more traditional "set it and forget it styles of management and governance, which are slow to change and better suited for more stable and consistent environments, adaptive management seeks to be nimble in the face of uncertain and constantly evolving risks. Through a continuous cyclical feedback process of monitoring the system, implementing a strategy, analyzing the impacts of that decision and any changes the system may have created endogenously, and recalibrating the implemented strategy in light of that new information, decision makers who use adaptive management are much better equipped to foster robust and resilient systems in the face of complexity and uncertainty (Biggs, Schlüter, and Schoon 2015).

The CAS perspective has been incorporated into the study of underlying systems such as health care (Hill 2011), supply chain (Surana et al. 2005; Crucitti, Latora, and Marchiori 2004; Pathak et al. 2007), technology and cyber (Phister 2010), and the financial system (Mauboussin 2002; Levin and Lo 2015; May, Levin, and Sugihara 2008), among others (Holland 1992). By similarly extending this perspective to GVCs—systems of systems composed of underlying systems that are themselves CAS—systems theory can provide greater robustness and resilience in the governance of GVCs. Within global industries, individuals, companies, governments, and other entities with the governance power to guide the industry focus on those outcomes they can control. However, as industries have evolved into GVCs that are increasingly interconnected with—and reliant upon—sprawling global networks of suppliers and consumers, and as these sprawling networks themselves depend on underlying global systems, these industries are less in control of their own outcomes and risk profiles. Unexpected behaviors and decisions of other actors within these interconnected GVCs can result in shocks that ripple across these network links, often amplifying as they strike other nodes.

Systems theory allows us to manage for these shocks by encouraging iterative governance practice through adaptive management, and by prioritizing the understanding of where one lies within a network, how healthy the other actors are in the network, and how predictable the links and flows are throughout the network. It requires not just a knowledge of the reliability of those to whom you are immediately connected but also an understanding of your

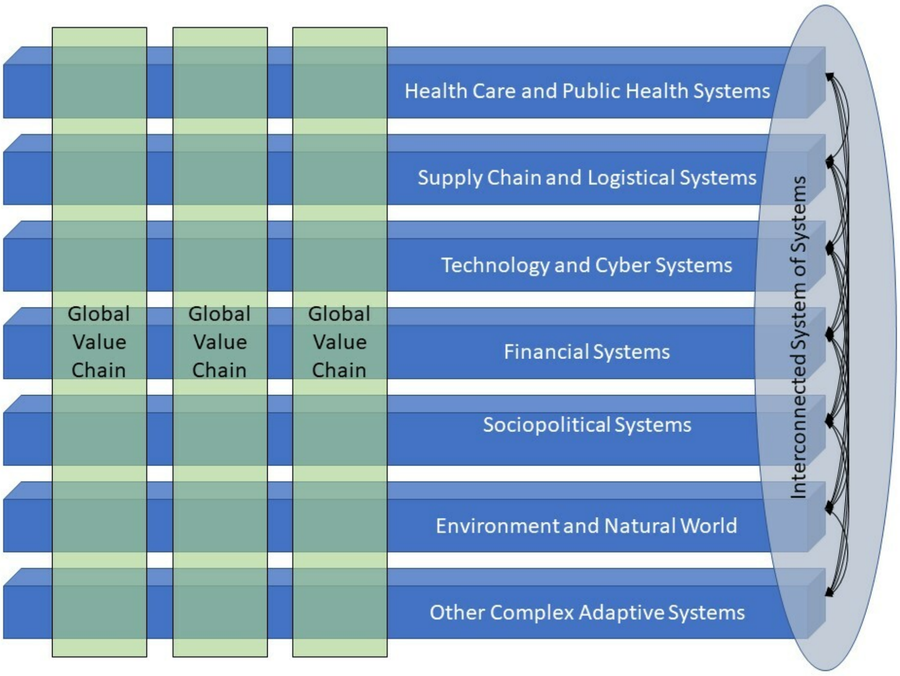

Figure 1. This diagram illustrates how GVCs are dependent and built upon a multitude of interconnected complex adaptive systems.

neighbor s neighbor and their risk exposure as well. By seeing each GVC as a CAS built upon an expansive network of multiple underlying CAS, it becomes clear that a systems approach is necessary to effectively understand their risks, undertake adaptive management in response to system dynamics, and inform systemic governance. Nations that develop such robust and resilient underlying systems are better positioned to attract GVCs.

ANALYSIS OF CRITICAL GLOBAL SYSTEMS

The following sections present examples of six major systems that GVCs typically rely upon to function: health care and public health, supply chain and logistics, technology and cyber, finance, sociopolitical, and the environment. These systems have been chosen to illustrate how GVCs depend on expansive underlying systems, each of which is complex and adaptive in its own right. This list is nonexhaustive as GVCs also rely on other critical underlying CAS, such as energy and electricity, food and water, infrastructure, and human and material transportation. By exploring the risks and uncertainties present in each of these chosen systems, we demonstrate that the foundation upon which GVCs are built can be easily disrupted. We show that the weakest links in a GVC might not be located along the chain at all, but may instead be found in the vulnerabilities of the underlying systems.

HEALTH CARE AND PUBLIC HEALTH SYSTEMS

The global COVID-19 pandemic has highlighted the importance of robust and resilient health care and public health systems. While good health for a population is a critical pursuit in and of itself, for the purposes of this analysis, we will examine it through the lens of industry impact and show that a strong underlying system of health care and public health is fundamental to the success, stability, and sustainability of GVCs.

Like the human body that it seeks to treat and maintain, health care is a CAS that relies on an intricate web of inputs and outputs to function effectively (Tan, Wen, and Awad 2005). The system balances the costly supply of facilities, equipment, medication, and staffing with demand that can change rapidly. Additionally, these systems must allocate resources while considering priorities of research and development, education, innovation, information technology, infrastructure, regulation, ethics, budgets, efficiency, and investment in prevention. This underlying system treats patients of every age with every type of injury, illness, disorder, and disease, making a “one size fits all approach impossible.

Adding to this complexity, the nodes and links in the system are constantly adapting as populations change, new ailments like COVID-19 are discovered and evolve, and new treatments, techniques, and technologies are introduced. While aspects of a health-care system like the number of hospital beds and the quality of doctors are important, so, too, are factors like water quality, sanitation, food security, and opt-out versus opt-in elements of public health that form the backbone of health care around the globe (Frieden 2010). Aging and outdated health-care infrastructures are clumsily enmeshed with modernized ones, while change and adaptation are frequently hindered by sclerotic bureaucracies, legacy technologies and methods, legal liability, medical insurance, other corporate interests, and tensions between public and private providers.

The COVID-19 pandemic tested the adaptive capacity of health-care systems around the globe to their limits. They had to be flexible enough to create more hospital beds and send PPE and staff to where they were needed most, nimble enough to change treatment strategies as evidence for the effectiveness of protocols like ventilators, different medications, and various supplements changed daily, and innovative enough to ultimately develop vaccines. When health-care systems are not successful in these efforts, the economic impacts can be devastating. World Bank analysis shows the West African economy suffered significant damage during the Ebola outbreak of 2014, driven largely by doubts that the health-care system could respond to further outbreaks (Bowles et al. 2016; World Bank 2014; Huber, Finelli, and Stevens 2018). The unprecedented scope and scale of economic impacts of the COVID-19 pandemic will take years to fully understand (McKibbin and Fernando 2020).

Companies planning to offshore operations must consider their new host country s ability to provide a resilient health-care system that enables productive and uninterrupted output. Research has long shown a positive connection between population health and productivity (Tompa 2002) and that businesses that prioritize the health of workers (and their families) will sustain gains in output and human capital. According to a 2005 study, labor time lost due to illness and other health issues accounts for approximately $260 billion annually in the United States alone (Davis et al. 2005). A healthy workforce takes less time off, works more productively, lives longer, and is proven to be good for a nation s economy (Dollard and Neser 2013).

While a threshold quality of public health is imperative for a nation to initially attract GVCs, this focus becomes especially important for nations seeking to “upgrade within a GVC by providing more skilled and highly educated workers who perform activities that produce more value further up the chain. In contrast to entry-level factory jobs at the bottom of the value chain, more skilled and trained laborers in “upgraded economies become more difficult and expensive to replace. In this way, the cost of lost productivity due to inferior health systems—higher instances of illness, longer recovery times, and careers limited by shorter life expectancies—also increases with higher-skilled workers.

As companies weigh the costs and benefits of offshoring, health care—which can represent a large share of labor-related costs—is a significant factor. Any benefits of reduced costs must be weighed against the potential increased risks to workers, and thus to the company, of working in a less healthy environment. Regulators like OSHA and laws that require health-care benefits for workers, for example, represent greater costs to industries, which might seek to base the lower-value elements of their value chains in regions where these costs are diminished. While critical for the attraction of more upgraded GVC activities, significant health-care costs and regulation could potentially dampen the development of lower-value activities within a country s borders. An industry might have manufacturing based in a less regulated health-care economy while the headquarters are in regions with more developed health-care systems.

As with each of the other underlying systems we analyze herein, health care is just one CAS within the interdependent system of systems that supports modern and globalized industry. A GVC s consideration of a potential new host country s health-care system must thus involve a comprehensive analysis of these systemic interactions. From the standpoint of nations working to attract new GVCs, while a minimal level of reliable health care is necessary to attract low-value work, significant investment in health-care systems may be required to attract high-value activities that enable upgrading within GVCs.

SUPPLY CHAIN AND LOGISTICAL SYSTEMS

The second underlying system we examine is the complex global network of supply chains and logistics. While a GVC involves all aspects of a particular industry—product conception, design, innovation, manufacturing, administration, marketing, and sales—a global supply chain typically represents the acquisition and delivery of tangible inputs for a single product sold by a single company. While the study of GVCs is often the purview of development economists and government officials hoping to attract global industries to their shores, supply chains are typically the focus of corporations that depend on inputs at all levels of production.

The modern economy has developed interconnected and complex global supply chains that transcend national borders and often require the concerted collaboration of multiple companies. This internationalization of supply chains is in large part due to benefits of comparative advantage, leading to the geographical specialization of production through outsourcing and offshoring. This specialization has given rise to the modern field of supply chain management, which has focused on efficiency and cost saving through supply base rationalization of activities related to physical distribution and materials management (Chopra 2003). Today, supply chains are often CAS dependent upon efficient logistics and intermodal transportation to deliver the right products to the right place in the right quantity at the right time (Choi, Dooley, and Rungtusanatham 2001; Surana et al. 2005). Adding to this complexity, differences in logistical capabilities, languages, cultures, currencies, time zones, laws, and other factors require highly technical coordination, information management, and regulatory compliance across borders.

As recently as thirty to forty years ago, companies managed supply chain risk by maintaining large warehouses, ample inventories, and rainy day funds of reserves, not knowing when and where they could reliably obtain production inputs. As firms became closely connected to others within technological and logistical networks, information visibility and rapid telecommunication allowed them to tie up less capital in these inventories and reserves. With growing confidence that they could obtain inputs from nearby suppliers—adjacent nodes in their networks—on a just-in-time basis, companies put trust in the system and removed internal redundancies as streamlining inventories became necessary for competitiveness (Vokurka and Davis 1996; Golhar and Stamm 1991).

Without this excess slack, companies have become less self-reliant and more dependent upon the systemic flows received through connecting links from neighbors in their network (Purvis, Gosling, and Naim 2014). By "living at the margin —focusing on whether they have just one more unit on hand—companies have been able to achieve greater efficiency, lower working capital, and higher return on investment. These efficiencies, however, come at the cost of greater risk that the underlying supply chain system will experience shock and contagion if critical suppliers are unable to meet requirements. Lean inventories and just-in-time processes undermine the supply chains abilities to withstand supply disruptions by leaving little room for error when situations change. The end result is higher *expected* reward, but at the cost of greater systemic risk (Scheibe and Blackhurst 2017).

In this way, GVC reliance on global supply chains exposes industry to systemic risks by making purchasers more dependent on the success of contracted suppliers and their subsuppliers. The disruption of a critical link or node in a supply chain can propagate through this underlying system with a series of cascading failures that spread beyond the initial disruption location and ultimately impact overall GVC productivity. Changes in the stability of a single supplier or pathway could paralyze an entire industry if it is left without a source of critical parts, materials, or processes. A 2013 fire at the world s second-largest microchip factory, for example, created a global shortage that reportedly impacted Apple, Dell, Samsung, Lenovo, and Sony, while driving chip prices up by nearly 20 percent (Handy 2013; Garside 2013). A four-hundred-meter ship ran aground in the Suez Canal in 2021, obstructed cargo vessel traffic for six days, halted much of the global trade system, and held up over $10 billion in commerce each day (Raghavan, O Grady, and Hendrix 2021; Yee 2021). The 2011 Fukushima disaster interrupted the global supply of silicon wafers and critical auto parts (Lohr 2011; Fisher 2011). The Bangkok flooding of 2011 disrupted IT manufacturing across the world, while ash from the volcanic eruption of Eyjafjallajökull in Iceland in 2010 obstructed global air traffic for days (Jabbarzadeh et al. 2016). Political unrest anywhere along a supply chain may also result in significant costs and losses. Whether it is the bombing of Saudi oil facilities, street protests in Hong Kong, or the collapse of the Venezuelan economy, these seemingly "local disruptions to supply can easily become global, impacting an entire GVC.

As CAS within the larger global system of systems, supply chains are vulnerable to emergent shocks that develop endogenously within the system as well as to disruptions that develop exogenously. Natural or human causes (or a combination thereof) such as pandemics, economic recessions, financial crises, technological failures, political unrest, strikes, regulatory issues, terrorist activities, simple bad luck, and "normal accidents can jeopardize key links or nodes from a supply system upon which global industry relies (Scheibe and Blackhurst 2017). A systems approach focusing on these fragile nodes and links recognizes that the integrity and reliability of supply chains are foundational to the resilience of GVCs.

TECHNOLOGY AND CYBER SYSTEMS

Risks in underlying technology and cyber systems are the next vulnerabilities we explore. Technological improvements and recent advancements in information and communication technologies (ICT) have changed the geographic boundaries of production and made participation in GVCs inevitable for both companies and nations. Companies within industries must face the reality of the effects of globalism on competitiveness, while nations similarly see the undeniable advantages of joining and upgrading within GVCs. These globalizing technologies, however, expose firms operating within GVCs to risks previously shielded by market boundaries and geographic distances while increasing the scale of information asymmetry (Gereffi and Luo 2015).

GVC activities like production, manufacturing, and logistics have become reliant on digital control systems. The current trends of automation and data exchange are driven by cyber-physical systems—wherein the operation of physical equipment is monitored and controlled by algorithms—that communicate and cooperate with each other in real-time both internally and across organizations of the value chain. With the increased use of the Internet of Things (IoT), cloud computing, and artificial intelligence (AI), these cyber-physical control systems can create a virtual copy of the physical world in which operations can be modeled, replicated, and simulated. From these virtual models, algorithmic decision-making processes can be developed that are both self-optimizing and decentralized.

As human agency is removed from this process, this high level of automation makes GVCs susceptible to failure as a result of algorithmic controls and the binary on/off nature of automation s operational components. GVCs with linear configurations where a large share of the industry s product, processes, and information flows through a critical node or hub create a system that is only as strong as the technological fragility of its weakest link. Whereas in supply chain fragility, GVCs can be interrupted by the failure of a node or absence of physical goods, in ICT fragility, production can similarly be halted by the presence of bad information or the failure of information processing technology. Crashes from "normal accident factors are increasingly inevitable given the technological complexity and tight-coupling characteristics of the system (Perrow 1984).

A single GVC can rely on multiple ICT networks—both private and public—leading to increasing complexity, with the possibility that traffic could either be split across different types of networks, or alternate back and forth. Each network comes with its own set of characteristics and procedures, making it challenging to collectively address the risks, as connected communication networks contain multiple nodes and links, each of which is a potential failure point. Underlying technological systems, such as power grids and transportation systems, increasingly concentrate traffic on open-access networks (OAN), where infrastructure is no longer proprietary and captive to a single supplier, but instead is opened up to multiple suppliers to offer consumers competitive options. While this concentrated traffic is more efficient, the reduced redundancies create risk exposure (Zhu and Basar 2015).

As CAS, these cybernetworks contain within them potentially catastrophic endogenous vulnerabilities that can emerge organically and spontaneously through the failure of nodes or links during routine system operation (Mittal 2014). Systemic fragilities can also be exposed, exacerbated, or triggered by exogenous shocks from external actors or the environment. These exogenous shocks can be caused by rare events such as severe weather, natural disasters, or intentional malicious attacks on technology infrastructure and cybersecurity. The exogenous shock of the 9/11 attacks on New York, for example, triggered a cascade of network failures that crippled internet service as far away as South Africa (National Research Council 2003).

Cyberattacks can range from "soft attacks, where viruses, fraud, and hacking create interruption, to "hard attacks that stop communication by physically destroying information and electricity infrastructure (Cameron 2020). Both modes of attack could affect supply chains, manufacturing, payment systems, GPS tracking, and the delivery of goods and services through vulnerable infrastructure. Such cyberattacks can take multiple forms like denial of service (DoS), man in the middle (MitM), eavesdropping, password phishing, and malware. Examples of recent failures can be seen in Wikileaks, "Shadow Brokers, WannaCry, ransomware, and identity theft in accounts related to Target, Uber, and Deloitte (Lanois 2019; Dreyer et al. 2018; Amoroso 2010). While many engineering efforts work toward designing robust and resilient technological and cyber systems, it is costly and impractical—if not impossible—to achieve perfect security against all possible attacks and events. This leaves us with a Hobson s choice: "we have no choice but to trust [computer technologies] completely, and it s impossible to verify that they re trustworthy (Schneier 2019).

Despite the risks, these rapidly developing systems have become critical to the success of GVCs today. Global industries were able to continue operating during the COVID-19 pandemic solely because of technology and cyber systems. Lockdowns, work from home, and limited travel—which might otherwise have halted many global industries—were circumvented by video calls, cloud computing, and global information systems. Many of these advancements in computing speed, internet bandwidth, cellular communications, and video conferencing would not have been available as recently as ten years ago. This increasing reliance on technology systems is likely to become a continuing legacy of the pandemic, heightening the value of the robustness and resilience of cybernetworks.

FINANCIAL SYSTEMS

Next, we explore the risks to GVCs from the underlying financial system. GVCs rely on funding provided by the financial system, where money passes through multiple steps or layers, from the individual or institution who saved and then lent out capital to the companies who borrow it for the production of goods or provision of services. The global financial crisis of 2007–8 (GFC) demonstrated the fragility of our financial system and its potential impact on global industry—an inevitable consequence of the complexity and opacity of interactions within global financial networks (Chambers et al. 2019). The evolution and expansion of the financial system through modernization and globalization ultimately resulted in network collapse during the GFC, which slowed global industries and triggered a worldwide economic recession.

Financial systems have historically enabled access to capital provided by savers to those who wish to temporarily lease this money in order to purchase assets and build productive businesses. Borrowers would then return this capital, provide a return to the saver, and claim for themselves any upside beyond the cost of borrowing. Banks originally lent locally and directly to individuals and firms, and in turn, the borrowers would be willing to pay an appropriate risk premium to rent this capital, a percentage calculated based on the bank s specific knowledge and analysis of the risk profile of the borrower. Since these savers often did not know the risk profiles of the borrowers, these banks stood in between—as "intermediaries —in order to provide this research and expertise. Over time, banks and other asset managers, as financial intermediaries, created networks of depositors and borrowers to allocate capital to the investments that provide the highest expected return for a given level of risk.

As technology, communications, travel, big data, and risk management advanced, these financial intermediary institutions realized that they could find *sources* of capital from remote markets instead of from direct depositors, and could find *uses* for this capital with firms that could employ it in similarly geographically distant locales. Financial institutions realized that after making these loans, they could sell them to other banks that would aggregate diversified and uncorrelated pools of loans and investments, thereby reducing the risk to the seller s own balance sheet. Local retail banks could now sell their loans to global financial institutions. In this way, money could travel through a chain of financial institutions, claiming an additional return at each step, much like a product gaining additional value as it travels through a value chain. The incentive for this iterative process of pooling loans follows a fundamental principle of finance: the value of a loan or bond increases as its risk falls and its probability of being fully repaid increases. The theoretical value of the pooled loans would increase each time risk was ostensibly reduced through aggregation and diversification. While the mathematically calculated theoretical risk of these massive loan pools was declining, this illusory risk reduction through financial engineering incentivized fundamentally irresponsible lending and increased risk-taking.

These increasing risks reached a tipping point during the GFC as actors at each level in the financial network made unsafe bets. Mortgage brokers and retail lenders infamously made loans to borrowers with no assets, incomes, or jobs. Large financial institutions purchased mortgages and other loans—essentially repaying the lender—in order to pool, package, and resell these direct loans in complex securitized products. These financial products included such derivatives as collateralized mortgage obligations (CMOs), collateralized debt obligations (CDOs), and asset-backed commercial paper (ABCP), among others. Banks, insurance companies, and other financial institutions created derivatives of derivatives, such as credit default swaps (CDS), creating further systemic interconnectedness, complexity, opacity, and systemic fragility. Firm-specific risk increased as banks not only manufactured but also invested in these products, often borrowing money to purchase them in highly leveraged transactions (Blinder 2013; Haldane 2009; Glasserman and Young 2015). The financial system as a whole—acting as a CAS—became more fragile as the interactions and dynamics between nodes became more byzantine and unpredictable.

During the GFC, the growing number of enigmatic financial products and transactions created emergent fragilities in the global financial system, which led to a widespread endogenous cascading failure, absent any malice or exogenous shock (Gorton and Metrick 2012). Countless iterations and complex layers of reborrowing and relending the same dollars were added between the depositors and the investors who ultimately employed this capital in productive activities. While diversification reduced the risk in theory, the complexity, lack of transparency, massive scale, and erosion of lending standards culminated in a catastrophic failure of the global financial system, which was rescued only through a government bailout.

A CAS approach to the financial system shifts attention away from the individual firms to instead focus on the relationships between them (Billio et al. 2010). Through the lens of network theory, this approach examines the links and dynamics between the financial firms rather than just the nodes in the network—the firms themselves. Macroprudential understanding of systemic risk requires monitoring the relationships between financial firms through their exposure to not just immediate counterparties but also second-order and higher-order effects—the counterparties of their immediate counterparties, and so on. Since continuous access to debt and equity capital is foundational for global production and commerce, such a CAS understanding of the risks in the global financial system is critical to the resilience of GVCs.

In recent years, global financial systems have continued to evolve. Cryptocurrencies, commission-free stock trading platforms like Robinhood, and other financial technologies (fintech) have increased the number of actors and created challenges for the regulatory landscape of our financial systems in significant ways (Yadav 2020; Madi 2019). These are important reminders that as systems change, new risks emerge.

SOCIOPOLITICAL SYSTEMS

Globalization s increasing number of bilateral and multilateral relationships, and the effects of these relationships on the political, social, cultural, and economic dynamics *between* and *within* nations, have added an important layer of sociopolitical complexity to GVCs. In many nations, large companies have increasing influence over policy—such as trade, tax incentives, and environmental and labor regulations—while industry groups are often formed to advocate on behalf of GVCs on issues where power is fragmented and interests are shared across participants. The power dynamics and relations between the government and the private sector are constantly rebalancing, as globalization has complicated the negotiating power of the parties. Industries that at one time were captive to their home countries now have the opportunity to renegotiate or walk away. Similarly, countries can present competing offers in their attempts to attract GVCs or upgrade their existing positions within GVCs. These economic benefits of globalization, however, have exposed GVCs to sociopolitical risks. The COVID-19 pandemic presented a powerful example, as governments effectively suspended or canceled existing contracts and arrangements and withdrew from trade relationships in order to prevent the export of supplies needed domestically (Pauwelyn 2020; *Economist* 2020).

The global interconnectedness through trade agreements, contracts, and historical relationships creates a CAS of governments, institutions, and businesses whose links represent political cooperation and collaboration (Morin, Pauwelyn, and Hollway 2017). Often when a relationship link between two parties is severed, it is replaced with a new alliance. In this way, the network graph is drawn and redrawn as global sociopolitics evolve. Through this systems analysis framework, we see how the flow of goods and services, provision of capital, migration of labor and jobs, and issues of international political economy can alter the structure and dynamics of this underlying global sociopolitical network. While GVCs seek stable environments in which to operate, the unpredictability and emergent properties of the ever-shifting geopolitical system create unavoidable fragilities.

A powerful visualization of this systemic fragility is the extreme concentration of tangible trade flows that pass through a small number of choke points (e.g., the Panama Canal, the Strait of Hormuz, the Strait of Malacca, the Suez Canal), effectively enmeshing the interests of many industries and nations in unprecedented ways. Even a short-term geopolitical disturbance at any of these choke points would reverberate throughout GVCs and affect the production of goods in seemingly unrelated and geographically distant locations.

A similar fragility may be exposed through analysis of global labor flows. For example, restrictions or increased labor regulation on guest workers from Southeast Asia could spell disaster for the Persian Gulf economies that satisfy 75 to 80 percent of their labor needs internationally (Connor 2016). Similarly, restrictions on US work visas and immigration from the Philippines would drastically impact the US health-care industry, which is increasingly dependent on international workers (Brush and Sochalski 2007). While the number of temporary guest workers and the amount of permanent economic migration from developing nations toward more developed economies have increased with globalization, many jobs have moved in the opposite direction through outsourcing and offshoring. Variances in cost of living and wage rates worldwide, along with advancements in transportation and communication technologies, allow firms within GVCs to chase efficiencies by offshoring their operations, and therefore their workforce. Evidence suggests that decoupling labor from a firm s physical location can have significantly positive impacts on firm market value (Jiang, Belohlav, and Young 2007), but the zero-sum nature of these job markets—where a job gained in a developing country from offshoring corresponds to the loss of a job when a domestic factory is shuttered—necessarily creates risk of conflict and discontent when employment is moved abroad.

Differences in labor regulations around the world can also be a source of sociopolitical conflict. The relative lack of transparency, traceability, and accountability of working conditions in many geographically dispersed regions can create serious challenges to GVCs. Scandals related to job fairness, unsafe and exploitative work conditions, and human rights issues have led to major boycotts. Two examples are Apple s sourcing from Foxconn in 2012 and Benetton and Mango after the death of 1,100 workers in the 2013 collapse of the Rana Plaza in Bangladesh (Harris 2012; Manik, Greenhouse, and Yardley 2013). Concerns about harassment, modern slavery, human trafficking, refugee abuse, sweatshops, and child labor rightfully create risk to GVCs and their profitability, and exemplify how sociopolitical pressures can impact global industries. Even when such unacceptable labor conditions are identified, GVCs face conflicting institutional demands created by the multiple stakeholders involved, where questions of political economy capture the conflicts between competing constituencies (Greenwood et al. 2011).

Reliable manufacturing and shipping also require political stability in order to assure both investors and customers. Buyers searching the globe for a source of inputs must consider the possibility of political disruptions endangering their suppliers. Despite efforts to predict political disruptions, such analyses remain unreliable and potentially costly. The failure of social science to predict the 1973 OPEC embargo, the fall of the Warsaw Pact, the 9/11 attacks, the Arab Spring, the 2019 Hong Kong protests, or the effects of the COVID-19 global pandemic means that any efforts to assure continued supply will depend on the ability of governments to guarantee sociopolitical—and therefore economic—stability. As manufacturing has increased in areas outside the OECD, the danger of politically related GVC disruptions has grown. Even among wealthy countries, tariffs, sanctions, embargoes, and trade deals all have the potential to seriously impact the continued flows of goods.

While the sociopolitical system has suffered shocks in recent decades during the rise of GVCs, this period has been relatively stable when examined through the lens of history. The nearly eight decades since the Second World War have been characterized by historians as the “Long Peace —an unprecedented period of global sociopolitical stability (Gaddis 1987). Industries have taken advantage of this relative peace and have been able to expand their operations across borders, oceans, and continents to create truly global businesses. While large-scale world war has not been an issue for some time, risks of international conflict are still significant, and disagreements about trade, labor, and geopolitics could devastate the global economy. GVCs must weigh the benefits of relocation to distant nations with the risks that regional or geopolitical instability could halt the production or transportation of goods. Sociopolitical systems can either facilitate global industry or make it impossible; an awareness of their complex and evolving system dynamics is critical to GVC sustainability.

ENVIRONMENTAL AND ECOLOGICAL SYSTEMS

Finally, it is also critical to appreciate the physical and spatial contexts in which GVCs operate. As with all complex interactions, GVCs depend on predictability and certainty, and global climate and environmental conditions can be challenging to prepare for. Given that relationships within GVCs often involve large sunk costs, while at the same time requiring the ability to pivot quickly in both product makeup and origin, it is vital that the environment in which they operate remain as stable as possible. The CAS of climate and ecology (Levin 1998) can be volatile, however, and make this stability hard to achieve at the best of times. Global climate change has only made this more difficult as weather becomes less predictable and the frequency of unexpected and extreme events increases. Additionally, the disruption of historical patterns such as Pacific monsoons and the North Atlantic Current makes guarantees of timely delivery challenging (Levermann 2014; Kuppam and Mawsynram 2019; Hickey 2018).

With approximately 90 percent of global trade carried by ship, seaports are a critical component of GVCs, and are a concrete example of how global industry is vulnerable to risks related to climate change (IMO 2011). Analyzing data from the past several decades, researchers have found that an average of 130 ports are impacted by large-scale storms each year (Becker et al. 2012). More than 30 percent of all seaports are located in tropical storm–prone parts of the globe, and the impacts of these storms can be devastating (Becker et al. 2018). In 2003, for example, Typhoon Maemi shut down South Korea s Port of Busan for ninety-one days (Lam, Liu, and Gou 2017). Hurricane Katrina caused approximately $1.7 billion of damage to ports in Louisiana, while the nearby Port of Gulfport in Mississippi continued to operate at only 80 percent of its pre-Katrina capacity for at least five years after the storm (Becker et al. 2012; PEER 2006). Hurricane Ike caused $2.4 billion of damage to ports in Texas, and Hurricane Sandy closed the Ports of New York and New Jersey for eight days (FEMA 2008; Becker et al. 2018). These powerful and destructive storms are examples of emergent shocks that grow from the complex internal dynamics of the global climate system.

In addition to the increased intensity of storms, sea-level rise is another side effect of climate change that could disrupt seaport logistics and, in turn, the GVCs that rely on them. In the Caribbean, for example, 35 out of the 44 ports that serve the islands and neighboring markets would be inundated with one meter of sea-level rise (Simpson et al. 2010). While higher sea levels and melting ice are expected to make new shipping routes available in Arctic regions, there is clear evidence that existing transportation infrastructure will suffer with rising water (IPCC 2019). For example, bridges that offered sufficient clearance for large cargo vessels might no longer be high enough to allow them to pass, and lock infrastructure might need to be redesigned at significant cost (Gallivan, Bailey, and O Rourke 2009).

Beyond seaports, climate change can impact other critical components of a large number of GVCs, including the growth of food, food security, environmentally driven labor migration, the extraction of raw materials, transportation logistics, and even the demand for certain goods and services (Teixeira et al. 2013; IPCC 2019; Mearns 2010). In this way, climate and environmental systems can be considered part of the underlying system of systems upon which the global economy depends. To respond to these growing and interconnected challenges, there has been a push to establish new intergovernmental cooperation and even to develop a new field of study of “adaptive logistics, which focuses on preparing supply chains and logistical systems for the potential complex dynamics and unpredictability of climate change (McKinnon and Kreie 2010; Nursey-Bray 2016). Impacts of climate change on commerce worldwide require prudent planning for a more uncertain future to develop resilience within.

Other environmental changes unrelated to climate can also have significant impacts upon GVCs. Research, innovation, and technology have led to advancements in agricultural science and methods. Many of the advancements, however, have led to a decrease in the diversity of crop species, as well as increased geographic specialization in export crops, making some “monocrop regions more vulnerable to bad seasons (Lin 2011). Increased global population and unsustainable resource management have led to overfishing, deforestation, overmining, and massive pollution—a global tragedy of the commons. Much GVC governance is shortsighted and self-interested—with a high discount rate—and does not account for systemic environmental concerns that play out over longer time horizons.

CONCLUSION

A systems approach allows us to view GVCs within their larger structural context, recognizing GVCs as CAS reliant on a series of critical underlying global systems. Through this CAS framework, we analyze the multilayered vulnerabilities within GVCs where system structure and dynamics create inherent fragilities. By exploring empirical examples of six underlying systems in detail, we illustrate how GVCs depend on a multitude of complex systems to function properly, and how the vulnerabilities present within those systems are passed on to the GVCs.

As GVCs have allowed industries to increase in scale, global range, and the integrative complexity of their networks and relationships, the risks they face have become magnified as well. The systemic risks we explored in health care and public health, supply chain and logistics, technology and cyber, finance, sociopolitical, and the environment illustrate how these risks do not exist in isolation. Instead, they are passed on from one system to the next and expose GVCs to systemic vulnerabilities they may not be prepared for.

Once these vulnerabilities are recognized, concepts, tools, and methodologies from systems theory can be applied to help bolster overall systemic resilience. By introducing principles of adaptive management, for example, critical system operators can foster nimble systems that are flexible and quick to adjust during times of complex uncertainty. Additionally, by recognizing the pitfalls of overefficiency and the dangers of systemic characteristics like tipping points, emergence, and normal accidents, system participants can help promote business practices that focus on sustainability and longer-term stability. With awareness of these systemic characteristics, decision makers can recognize that often no single entity or individual is responsible for critical system maintenance, let alone for how these critical systems interact with one another, and that GVC stability is a collective action challenge outside the immediate control of its participants. In this way, risk mitigation in CAS requires an awareness of broader systemic structure and characteristics: knowledge of one s position within the system, which other systems are integral to their success, and the consequences of rapidly changing interactions between critical links and nodes.

While globalization presents costs and risks—cultural, social, environmental, financial, and political, among others—countries that successfully join and upgrade within GVCs gain greater power within the global economic community, provide opportunity to their labor forces, and thereby alleviate poverty. As nations and development economists seek to expand the reach of GVCs, this CAS approach provides a framework for designing resilience within underlying systems, and therefore within the GVCs acting as systems of systems. Developing nations seeking inroads into GVCs can apply this methodology to design and construct systems that manage the tensions and trade-offs between efficiency and resilience. As the potential costs of interruption and failure rise with the increasing scale, scope, and complexity of global industry, nations that offer a sophisticated understanding of systemic dynamics can position themselves to attract GVC investment and expansion.

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COMPETING INTERESTS

The authors have no competing financial or nonfinancial interests to declare. Centeno is *Global Perspectives* section editor for Global Epistemologies: Concepts, Methodologies, and Data Systems. He was not involved in the review process for this article.

Submitted: February 11, 2020 PDT, Accepted: June 13, 2021 PDT

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