VITAL FLOWS

Supply Chain Resilience in Treacherous Times

FREE DISTRIBUTION DRAFT

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Books previously written by Philip J. Palin include:

Catastrophe Preparation
(McGraw-Hill Professional Development series)

Out of the Whirlwind:
Supply and Demand after Hurricane Maria

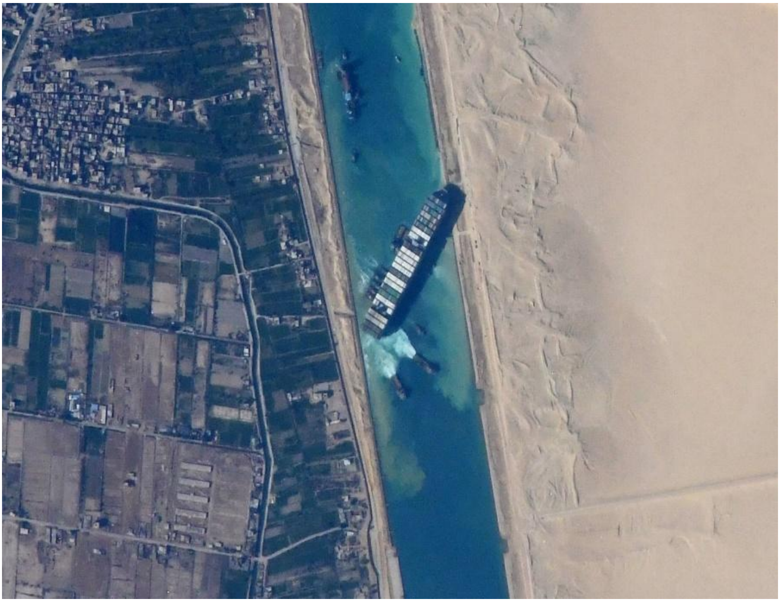
He Looks at the Earth:
Catastrophe, Recovery, and the Cascadia Earthquake

Flow and Not

Shoved and battered by a sandstorm the giant container ship *Ever Given* ran aground on March 23, 2021, blocking the Suez Canal for six days. Four football fields long, the ship can carry 20,000 TEU (twenty-foot equivalent unit) containers. On the day its prow plowed into the desert, *Ever Given* was about 85 percent loaded for passage from East Asia (departing March 13 from Tanjung Pelepas, Malaysia) scheduled to arrive at Rotterdam, Netherlands on April 3.

Most of the ship's stranded cargo consisted of "electronics, machinery and parts, household goods, furniture, and footwear" worth about $700 million. While wedged across the canal's single lane south of Great Bitter Lake, the *Ever Given* blocked transit by another fifty-plus ships per day. When the blockage began twenty-four crude oil tankers, fifteen refined product tankers, sixteen liquified natural gas/LPG carriers, and forty dry bulk cargo ships were already in line. In recent years, more than ten percent of total seaborn trade and almost one-third of global container traffic has transited the Suez Canal.

This busy, beautiful, aquamarine ribbon of water designed and built to save cost and time – up to three weeks around Africa – promptly became a global chokepoint. Each day dozens more ships coming and going from ports half a world away were required to drop anchor or risk a lengthy rerouting. The ambitious bottleneck intended to speed and target the pour of commerce was corked. Flow stopped.



NASA, photo from International Space Station, March 27, 2021

This sudden stop encompassed olive oil bound for Los Angeles, wastepaper traveling to Mumbai, at least 5000 containers of various auto parts (including elusive semiconductors), lap top computers, and even garden gnomes. The variety, banality, and huge volumes involved in global trade were unveiled to global stakeholders already unnerved by widespread pandemic-related flow complications.

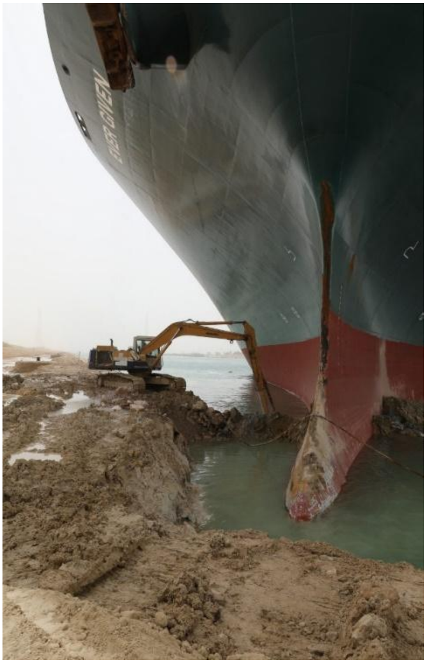
Every day and each hour supply chains are disrupted. High volume, high velocity systems slow, shudder, zig, zag, surge, or stagger to a stop. Complications are constant. Related delays, replacements, and fixes are ongoing. These are seldom noticed by outsiders, no matter how busy, courageous, and creative the insider efforts to preserve and restore flow.

This corking of Suez has, as Aristotle explained, metaphorical magnitude. The dramatic potential of the *Ever Given* reflects, even depends upon, the constant repetition of similar smaller-scale problems. What unfolded with the *Ever Given* is functionally recurrent across most demand and supply networks: Capacity is purposefully concentrated – bottlenecked – to reduce various costs and/or speed delivery. Given these concentrations, any intentional, accidental, or natural impediment can quickly multiply impact unless immediately mitigated – which is usually what happens.

What seems small and tedious when quickly resolved became monstrous when the fix was delayed, the flow was a high proportion of total flows, alternatives were unattractive, and network effects accumulated. As the disruption's magnitude became clear, so too did its strategic implications: the potential for small variations to violently explode was demonstrated one more time.

On the same day that the *Ever Given* caused back-ups in the Red Sea and Mediterranean, the ports of Los Angeles and Long Beach were in the first weeks of a logjam that would worsen for much of the next two years. Some of the containers on the *Ever Given* were contracted in a conscious effort to avoid the still-early LA/LB port congestion by sailing for the US East Coast through Suez. Best laid plans…

Regardless of magnitude, problem prevention *and* rapid mitigation *and* arduous fixes all typically depend on individuals. Abdullah Abdul-Gawad and the excavator he operated became potent symbols – and a *successful example* – of the very human dimensions of Supply Chain Resilience. (See picture at right.) Abdullah was essential, but not alone. Tugboat crews, *Ever Given* engineers, the emergency salvage team, dredge operators, and many more all had crucial roles to play. From the start there were also some who added complications and – unintentionally – made a bad situation much worse.



Suez Canal Authority

Tucked into the almost 18,000 containers on the *Ever Given*, surrounded by lawn mowers, bicycles, expiring tofu, and Ikea furniture were pallets of surgical gowns, face masks, and other durable medical goods. The covid pandemic's Spring 2021 wave would peak and break before these vital supplies reached Rotterdam.

After six days the ship was pried loose and refloated. Other vessels resumed transit through the Suez Canal. But the *Ever Given* was impounded for another three months a few miles north at Great Bitter Lake as the owners, operators, Suez Canal Authority, and others argued over responsibility, costs, and accountability.

I have never seen a comprehensive forensic analysis of the *Ever Given's* cargo. It is tempting to imagine a quick sweep of computerized cargo manifests finding seven high priority products that could be rapidly extracted and expedited to where most needed. But that is not how flow works.

While most garden gnome buyers and sellers might defer to surgical gowns, criticality – and therefore priority – can be treacherous to triage. With most high-volume flows even when there is enough insight or authority (dancing together can be helpful) to conceive "good" choices, the practical ability to choose is often constrained by stubborn realities. For example, in the case of the *Ever Given*, how deep into stacks of several thousand steel containers do you need to dig? Where do you start digging? And how do you extract the desired content when required tools are not available? (In this case a giant, multi-million-dollar crane plus related dock-side technology and trained operators.)

The larger any flow – and the more connections with other significant flows – the more such questions expose hidden realities. The more urgent the human need, the more these specific questions resist confident answers. The more expansive demand, the more such questions arrive at figurative and literal dead ends. As scope and scale expand, well-established flows reward participation and punish attempts to undo preexisting preferences. Flows constantly shift, swerve, slow, accelerate – in a word: change. But major disruptions or diversions – especially if sudden – almost always prompt fierce, unpredictable reactions from flow itself.

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This book is intended to help some of us – as many as possible – actively participate in constructively shaping system-wide supply chain preferences, flows, and outcomes.

What questions are well-suited for preserving and enhancing high volume, high velocity flows? What behaviors productively facilitate flows and fulfill human needs when major flows are disrupted? What strategies advance Supply Chain Resilience in treacherous times?

The story of the *Ever Given* is not idiosyncratic. This story is a meaningful case study for contemporary global supply chains. This story is a narrative template for how large-scale networks of all types can behave. What can we learn – do differently – when we encounter these and similar stories?

Supply chains are being revolutionized by urgent needs, intense competition, technological creativity, enterprise-specific investments, skilled (and less-skilled) management, and vast efforts to problem-solve—upstream to downstream from policy meetings to stock-aisles. But the revolution of the last quarter-century has been so fast and profound there is a dearth of whole-system understanding and related strategic insight. This book is intended to help close that gap.

Global-girthing flows have never been bigger, never been more important, and never been more vulnerable to disruption than in this century. The *Ever Given* case is a comparatively benign example of innate supply chain characteristics that rear their ugly heads with increasing frequency and burgeoning destructive potential.

No *one* owns the whole system. Well-intended regulations to mitigate risks often increase catastrophic probabilities. Collaborative efforts to cultivate strengths and weed out weaknesses are deeply fractured. So, it is not surprising there are rather few people who have anything close to a comprehensive view regarding the complex adaptive system that is blithely called "the supply chain". Of these few, even fewer are in decision-making roles that provide regular opportunities for choosing and implementing practical measures to advance resilience.

There are, though, people, places, and professions with significant influence on supply chains. There are principles and processes that have been effective helping supply chains with fewer unintentional consequences. There are even innate characteristics of contemporary supply chains predisposed to more resilient outcomes. Knowing how to deploy these predispositions can be powerful. So, this book tries to show how.

The first section of this book briefly outlines systemic preferences of demand, supply, and flow and my personal preferences for operational and strategic mitigation of systemic risks involving supply chains.

The second section of this book looks at five case-studies of actual supply chain behavior in catastrophic contexts for evidence to illustrate and clarify the preferences outlined in the first section.

The third section of this book integrates these preferences with real-world examples to offer a set of actionable strategic principles. By this point most readers will be ready to analyze, synthesize, and cultivate their own preferences and principles related to Supply Chain Resilience.

Finally, we will look up the trend-line into plausible system-level threats and implementation of effective risk mitigation strategies.

Philip J. Palin
December 2023

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PREFERENCES

A bias, partiality, leaning, or predispostion. An option chosen first from among other roughly similar options. 1A core characteristic that compels behavior. Derived from Latin *praefero* (*prae*: in front, *fero*: carried or borne).

WHAT DO YOU SEE?

Anglo-Saxon London (roughly 500-1066AD), developed by the Londonist (2011) using various historical records.

Same place more recently showing major roadways (Google)

Most of us have preferences. Many of these preferences have emerged from – or in reaction to – our earliest experiences. These preferences are especially robust if they have been consistently reinforced over time. The same is true for supply chains and other networks related to demand and supply.

Since the Suez Canal opened in 1869 it has become the preferred route between Europe and India then East through the Strait of Malacca. Overland connections, such as the Silk Road, and the much longer maritime Cape Route did not empty, but overall flows substantially increased as Suez reduced costs and risks. But the older routes could not – preserve their prior proportion of much smaller total flows.

The Suez Canal, constructed early in the industrial age, reinforced many of the commercial and cultural predisposiitons of its builders. Along the way the canal shaped – still shapes – commercial, economic, and geo-political possibilities and consequences.

I am the son and grandson of grocers. Growing up I cleaned stockrooms, sacked ice, delivered bakery products, mucked out meat department grease pits, picked up sundry supplies, tarred roofs, and reorganized freezer space. During a US beef shortage the frozen hamburger patties imported from Australia were spilling out of battered boxes. I spent most of a week in freezers repacking and stacking mottled-pink ice-hard industrially stamped discs, preparing to supply Fourth of July barbeques as best we could. At least we had hamburger patties when most of our competitors did not. Huge sales.

My early experience with the grocery stores still influences how I perceive – and engage – demand, supply, and flows that are generated by the interaction of demand and supply.

My dad walked away from his VA tuition benefits to help his dad save the stores. Grandpa resisted radical shifts in post-World War II consumer behavior. Dad closed most of the small stores in tiny towns to focus on saving two stores with the most potential. Two decades later when I left for college there were four large stores in two adjacent counties in the upper fifth of national income. By the time I finished college the same places and people had fallen two quintiles – and today occupy the lowest economic strata.

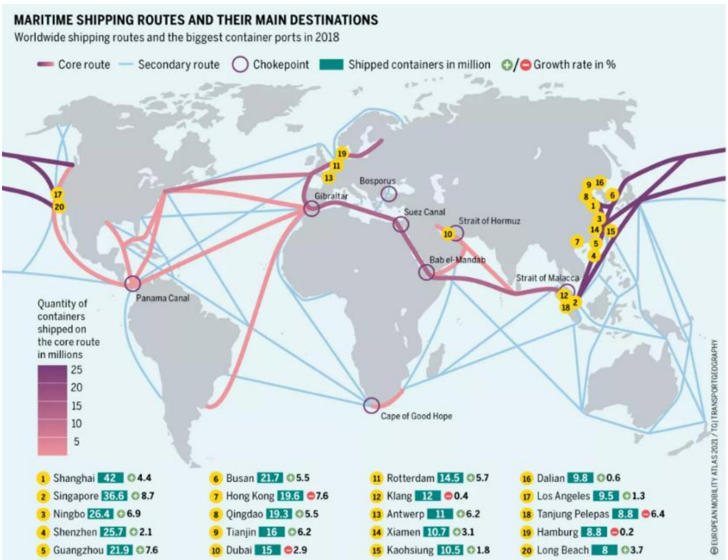
Dad, again, was agile, adapted, survived, and even thrived by claiming a much larger share of a much smaller market. It had long been clear I was not well-suited for the grocery game and, in any case, the game was fundamentally changing. I would not go home. Dad sold the stores at just about the right time. Now in his nineties, he and his crew help digital newbies use Ebay to access non-local demand interested in buying whatever locals have to sell. They started (after her death) with Mom's treasures. Dad also leases local properties to non-local suppliers, such as Dollar General, who – like the Suez Canal – have increased overall flows at lower cost and reduced risk compared to prior channels.

There are plenty more such origin stories. They tend to result in an angle on reality I find persuasive: Demand pulls supply. Supply pushes toward demand. Where demand is strongest – as measured by population and wealth – supply will be most abundant. Where and when demand weakens, supply will diminish. Major flows rise and fall with forces beyond any reasonable control. Change is constant. We can creatively adapt to change by being realistic about pull, push, persisting flow patterns, shifting flow patterns, available resources (especially relationships), and personal experiences that pop unpredictably.

This is my preferred angle on reality. This is my principal operating theory. This is my heuristic. The personal experiences that pop may be good or bad. The patterns emerging may be good or bad. What is happening may not be what I prefer to happen. But I have a preferred way of framing and interpreting what happens. I am very attached to this framing and method. It is my bias. It is the working hypothesis that I test and retest day after day, even minute after minute – especially during serious disruptions.

Given this angle, I start with places where people concentrate. I also want to know about how wealth and poverty are dispersed. Then I look for how these concentrations of need, want, and purchasing power are linked to sources of supply. There are usually concentrations of supply. I try to find the fewest supply concentrations that can get me to 80 percent of total flows. Five is the most common finding. More than seven is unusual. How are these key supply concentrations connected to demand concentrations, to each other, and, usually, to shared distribution channels running in between?

Bridges – both physical and virtual – fascinate me. The Suez Canal is essentially a water bridge connecting the Mediterranean Sea (and the Atlantic Ocean) to the Red Sea (and the Indian Ocean). Bridges almost always connect population concentrations – and the building of a bridge often creates a new population concentration associated with the bridge. The strength of this bridged "betweenness" can be fundamental to the patterns that emerge and the likelihood of patterns persisting.



Maritime shipping routes and their main destinations (Heinrich-Böll-Stiftung European Union)

On good days and bad these are the dynamics that I expect to play-out. When there are problems, this is the framing that I use to diagnose symptoms – looking to find a concentration that has become disconnected, the bridge that is broken, where and how pull and push have been separated. The differentiated diagnosis is almost always complicated and seldom certain. But – so far – this worldview and method seems mostly coherent with the way the world works.

Maybe this is because these preferences reflect the origns and predispositions of large scale, high volume, high velocity flows. Consider the map of maritime shipping routes on the previous page. The origin and destination points for the planet's top twenty maritime flows are identified. You may recognize more dense connections between places with proportionally more people and, especially, more wealth. The density of flows Is measured here by millions of containers. Containers are not the only mode of maritime transport, but altogether containers constitute a bit more than half of total flows (and are easier to count than other modes). Seven "choke-points" are circled.

Now look at either of the London maps on page 14. Places with more people are prominent. Some comparative concentrations are implied (or imagined or imposed?). Connections between places are shown. In some places these connections intersect. The older map's intersection at Padintune (more recently Paddington) is especially evocative. All of these intersections, old and new, skew toward the original London bridge. In this network, the original bridge is the core attractor, the primary"orig'n and destination. Our maritime cartographers might circle the bridge as a chokepoint. Choking is possible. But most days it is better described as a bottleneck: smoothing, speeding, and directing flow.

On the modern map there are now more bridges. In the last 200 years many different modes of transport have proliferated. Most are much more capacious and speedy that those used in 1066. But even a thouand years on, the pull of the original bridge (and its attendant population and wealth) still attracts and organizes push.

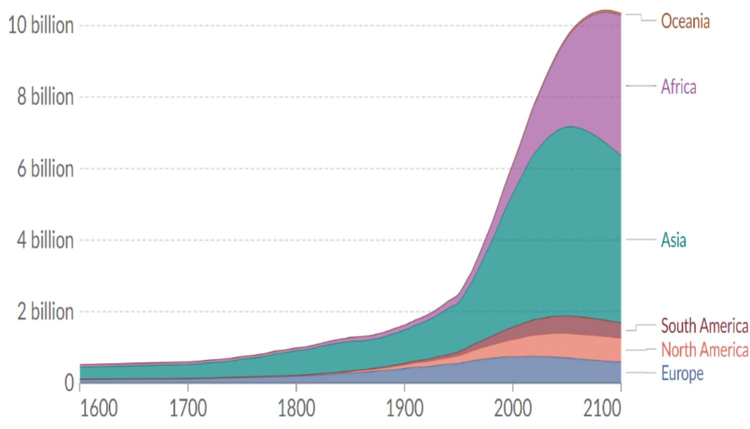
Like me, these flows have preferences. The flows are attached to and organized around long-persisting nodes, intersections, confluences, channels, and relationships. Ancient edges sometimes slumber but usually survive. These attachments are adaptable. The most persistent preferences tend to be indifferent to content and modality, it is flow-as-flow that insists on making its way. Preexisting flow is flexible, but very difficult to entirely escape.

At least this is my experience. This is the meaning I have derived from swimming into this flow.

Demand and Supply

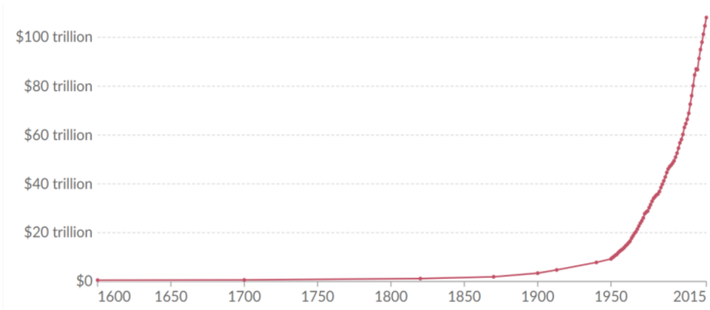
Both population and wealth have increased substantially over the last two-hundred years. In the last seven decades each factor has experienced explosive growth. For the remainder of this century the population growth rate is expected to slow and, in some places, start to decline. Economic growth is more difficult to confidently project. The chart on the next page offers alternative scenarios. In any case, the structures, systems, modes, and methods sufficient for supply to fulfill demand in 1950 have been revolutionized in response to these changes. Over the last thirty years the velocity (speed and targeting) of supply has – *necessarily* – increased at rates approximating or exceeding population and wealth.

World Population



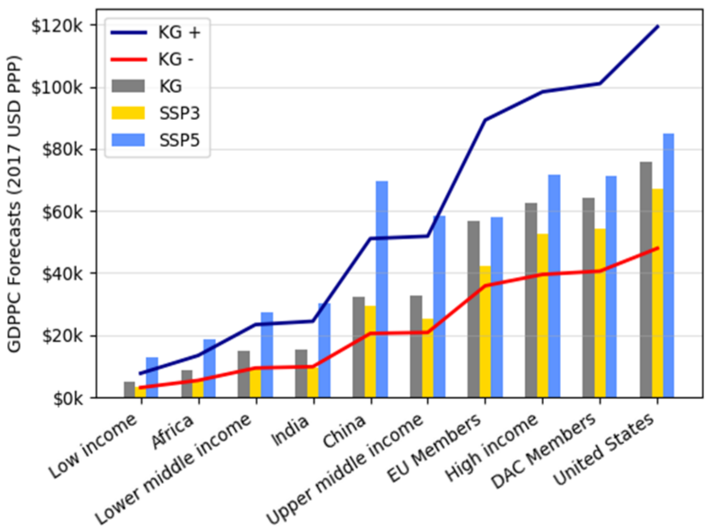
Charts above and below: Our World in Data (University of Oxford

World Gross Domestic Product (2011 constant dollars, adjusted for inflation)



Global Economic Growth Scenarios and Projections

KG+, KG-, and KG: Charles Kenny and Zack Gehan in *Scenarios for Future Global Growth to 2050*, Center for Global Development, March 2023. Shared Socioeconomic Pathways (SSPs): Projections developed by the Intergovernmental Panel on Climate Change



In my lifetime there has been a sharp increase in the need for water, food, clothing, energy, shelter, and healthcare. As a result, there has been sharply increased demand for freight movement and related transportation capabilities. In many places, there has been an even more robust increase in wealth. This has spurred demand for goods and services far beyond fundamental human needs.

To fulfill this rapid and profound increase in demand it has been necessary to accurately anticipate demand dynamics: who wants what, when, and where.

From the early 19th Century until now increasingly speedy material handling capabilities, such as railways and steamships, have more quickly moved larger quantities longer distances in the general direction of *potential demand*. Beginning in the last quarter of the 20th Century Supply Chain Management and related technology emerged to improve our ability to target and time delivery to *proven demand*. Supply Chain Management organizes production, processing, and product movement to fulfill demand when and where consumers are ready and able to pay costs plus whatever margins can be successfully applied.

This sustained non-linear – rocketing – surge in demand volume has required radical changes. Today's complex adaptive network of demand and supply is significantly different from how goods flowed prior to 1950. Since 1990 the supply chain's transformation has accelerated. Since the advent of smart phones in 2007, consumer expectations regarding speed, convenience, and personalization of supply – in a word: velocity – are further twisting and turning supply structures, systems, modes, and methods.

More Impatient People with More Money in Tighter Places

Each Christmas, for many years, the extended family gathered at my dad's parents' house. Almost without fail during the gift-giving rituals my dad or one of his siblings or a Great Aunt or Uncle would pronounce, "It must still be on the Hayes Truck," prompting giddy laughter among my older relatives. Finally, I asked about the inside joke.

Christmas is a busy season for grocers. When the day arrived, my grandpa did not always have a gift for everyone on his Christmas list. More than once he apologized and explained the gift was "still on the Hayes truck." From 1922 to 1975 Hayes trucks delivered mixed freight across rural Central Illinois[1]. Grandpa's claim may well have been valid. But true or not, "still on the Hayes truck" became my family's shorthand for not yet but on the way, somewhere out there in the unknowable world beyond our reach.

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[1] Hayes Freight Lines was notorious for slow, unpredictable, randomly routed deliveries. In the early 1950s the firm operated nearly 2000 motor vehicles, employed more than 2000 persons (736 serving its Illinois intra-state operations,) and maintained terminals at thirty-five cities in eight States. In one year, Hayes trucks made approximately 60,000 vehicle trips over Illinois highways, traveling a total of 90,000,000 miles, and transporting daily 7,500,000 pounds of property. In one twelve-month period Hayes trucks were cited for 157 violations of Illinois weight limits and the State suspended its license to operate in Illinois. The legal case was eventually decided by the United States Supreme Court: see *Castle v. Hayes Freight Lines, Inc*., 348 U.S. 61 (1954)

Five days ago, I ordered a gift. I received regular digital updates on my "free" shipment until it arrived yesterday, one day earlier than promised. Thanks to the commercial application of various Cold War technologies, including satellite communications, the Global Positioning System, cellular networks, and high-speed computing, I can keep track of where my purchase is at, where it is going next, and when it is scheduled to arrive. This expectation is generally achieved or exceeded.

This is reassuring. It encourages confidence regarding my next online purchase. It is also a comparatively inexpensive consumer-facing service spawned by a very expensive set of technologies absolutely essential to achieving the velocity needed to deliver today's volumes at an affordable rate. Walmart destroyed Sears by mastering these tools for effectively targeted, well-timed, efficient large-scale warehouse to store deliveries. Today Amazon and Walmart (and others) are competing to deploy these and related tools for even better just-in-time, personalized, price-competitive demand fulfillment.

These concepts, technologies, and methods are crucial to competitive advantage because they are also fundamental for serving the high volume, high velocity demand that has emerged in recent decades. For five thousand-plus years excess supply wandered wishfully in search of potential demand. Today real-time and statistically probable demand determines supply and generates planet-girding flows.

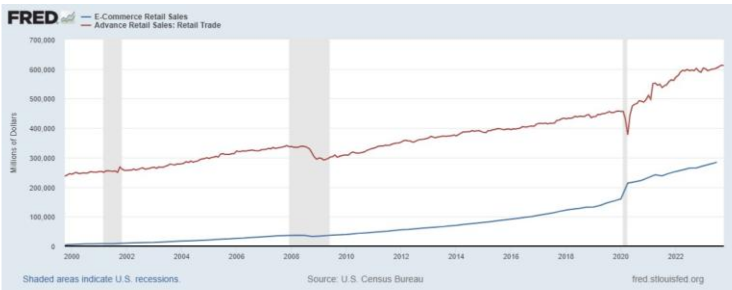
In November 2023 Walmart's CEO, Doug McMillon, summarized third quarter outcomes:

> "We're on track to grow adjusted operating income at a faster rate than sales for the year… We had strong revenue growth for the quarter across each of our segments. Comp sales for Walmart U.S. were 4.9% and 3.8% for Sam's Club U.S. Sales for Walmart International were up 5.4% in constant currency, led by Walmex and China. Sam's Club continues to perform well, both in Mexico and China… *E-commerce sales were up 24% in Walmart U.S., 16% in Sam's Club U.S., and 15% globally*." (Palin italics)

In this century online or e-commerce or digital (or whatever the preferred label) has transformed demand behavior. At the turn of the century e-commerce accounted for less than one percent of total US retail sales. By 2023, depending on what and how it is measured, e-commerce was the source for at least one-fifth of total US retail sales. According to Department of Commerce estimates (see first chart at bottom of the page) up to 47 percent of US retail sales can now be credited to online purchases.

According to Commerce 360, using Department of Commerce data, during 2023, "year over year, U.S. ecommerce grew an estimated 7.7% in the first nine months. Total retail sales increased 3.9% over the same period." Physical stores still push huge volumes. Consumers still pull most of their demand at and from physical stores. But since the proliferation of smart phones began in 2007, online has regularly outpaced the growth rate of brick-and-mortar sales (except for the late-pandemic bounce back from 2020's cratering of in-store sales).

Retailers have noticed and adjusted accordingly. The second chart below shows the slowing pace of Walmart's investment in new stores. Ninety percent of US residents already live within ten miles of a Walmart store. More stores would have a marginal impact on increased sales. More online investment is much more likely to generate increased sales. Real estate and employment costs can be contained.



Number of Walmart stores in the United States

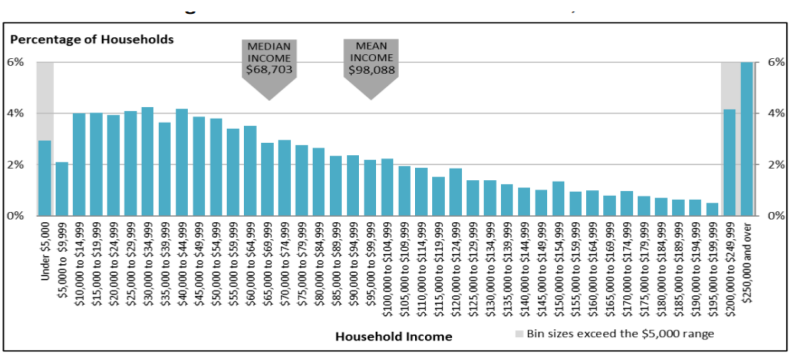
Today the fastest growing pull reflects the highest velocity push. Velocity indicates how fast *and* in what direction volume is moving. Many Hayes trucks (over-weighted or not) slowly carried comparatively small volumes rather short distances in response to erratic – arguably unsustainable – pull. Today UPS, Fedex, Amazon, and many others compete by delivering huge flows over *mostly* short distances – <100 miles roundtrip – to fulfill specific, even personal pull. The scope, scale, and recurring velocity of these flows, so-far reinforced by demographic and economic patterns, has created an abundant ecosystem of demand and supply unlike anything known just a half-century ago.

Since 1920 most Americans have lived in or near cities. In the 2020 US census, eight out of ten persons lived in urban areas. Increased density facilitates higher velocity push. With more consumers more concentrated, timely and affordable delivery is much more doable than serving geographically scattered populations. In 2022, according to the US Census Bureau, the residents of US Metropolitan Statistical Areas had an annual median household income of $77,500 compared to $55,900 for non-metro residents. In metro-area suburbs the median household income was $83,230.

But these all-population estimates may still under-represent the urban versus rural wealth effect. About ten percent of all US households (roughly 131 million) have incomes above $200,000 per year. More than 90 percent of these 13 million households are in metro-areas. This urban concentration of both population and wealth generates very strong pull velocity. Geographic concentrations of this population facilitate more sustainable push velocity. In November 2023 when Amazon announced expanded options for grocery home delivery the service was limited to (a gradual roll-out of) 3500 cities and towns.

I live at the top of a narrow mountain road about 15 miles from the nearest Walmart, over 20 miles from the nearest Whole Foods, and more than 40 miles from the nearest Amazon fulfillment center. The population density of my zip code is 72 persons per square mile. The population density of Philadelphia is almost 12,000 persons per square mile. Even sprawly Phoenix has a population density of 3100 PSM. The volume and velocity of pull in a dense urban environment creates the opportunity for high velocity push that does not exist elsewhere—and was certainly not available to a Hayes truck ala 1950 or 1960-something.

Distribution of US Household Income (2019)



Evolution of Demand and Supply Networks

In the 1930s and forties my family's grocery stores mostly purchased, processed, packaged, and sold a wide range of local products, especially perishables such as meat, dairy, and produce. Longer-lasting products – such as flour, sugar, salt, potatoes, onions, and canned goods – were likely to be delivered to some rail siding and picked up using our own trucks or by regional wholesalers that had exclusive contracts to re-sell name-brand products. We had a four-story warehouse and "the cave", cut into a hill to keep products cool. Well into the 1960s my grandfather and then father kept considerable reserve stocks to manage unreliable supply.

We also used our own trucks for specific – often opportunistic – bulk purchases from a distance. In May and June grandpa drove the biggest truck to Southern Illinois or even all the way to Georgia to purchase peaches. In December there was a roundtrip to Florida bringing back two or three truckloads of oranges, grapefruit, and Georgia pecans for Christmas. That would be the inventory for the entire season. No resupply. Go—get—return—sell—stop. No flow.

Mid-Twentieth Century trains and trucks could carry greater volume at faster speeds than donkey carts or camels. But in terms of structure and flow freight movement was not radically different than 500 or even 2500 years before, at least along the Mediterranean, Rhine, Danube, Euphrates, or

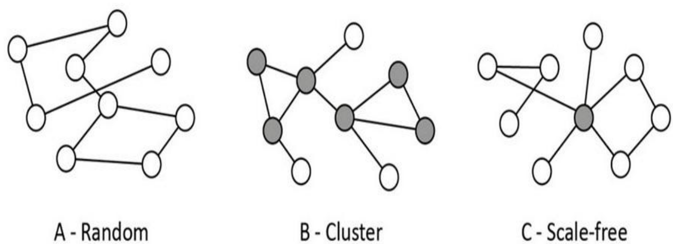
Yangtze. Water-borne freight offered something close to rail-like volumes and well-defined routes.

Five *thousand* years ago, a self-sufficient, extended family of farmers-hunters-gatherers occasionally transferred food to or from others in trade or as gifts. Especially if the family was physically isolated from others this kind of connection was unstructured… emerging from chance encounters… random.

Over time descendants of this family, as their population and that of their neighbors increased, had more frequent contact with outsiders. They began to gather at particular places on a recurring calendar for a variety of social purposes. Food and other items were traded or offered in religious rituals. Mostly random encounters were supplemented by connections that clustered in space and time. The biggest clustering was often periodic rather than persistent (consider medieval trade fairs), because of the costs involved in overcoming distance. Many dispersed populations were usually in relationship with several different clusters. Random networks and cluster networks describe most social and economic behavior of the last 300,000 years.

In the last 200 years as technology reduced the duration involved in distance, many more clusters have become perpetual with very active ongoing linkages. In the Illinois town of 1600 where my grandfather had his first grocery store there were usually at least two more grocery stores serving coal miners, surrounding farmers, and even some factory workers. Over the Twentieth Century both cluster-size and link volumes grew significantly. Today that town still has 1400 residents but does not have even one full-service grocery store. What residents once purchased from my grandfather, father, or their local competitors now requires a 10-to-15-minute drive to bigger stores serving more expansive areas.

With sufficiently dense demand, clusters are sometimes replaced by hubs. It is now estimated that each day sixty percent of US pharmaceutical supplies pass through Memphis. The FedEx hub at Memphis has something to do with this. So does a nearby national hub of a large pharmaceutical distribution firm. A hub differs from a cluster in the full network's level of dependence on the hub. A network where densely connected hubs are prominent is sometimes called "scale-free".



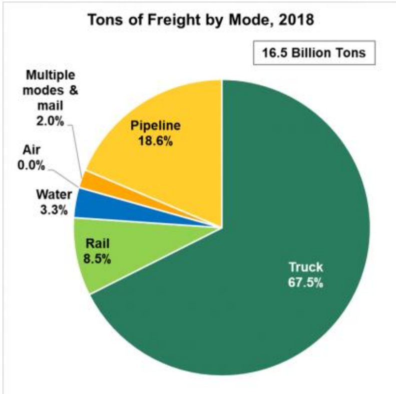
Above, from ***Bak's Sandpile: Strategies for a Catastrophic World****, Ted G. Lewis (2011)*

As volumes increase hubs can reduce network friction – often reflected in financial costs – by applying a variety of technological and human interventions optimized for product, place, or purpose. The greater the volume – such as pharma products flowing through Memphis – the more capacity and capability is developed and friction is further reduced, increasing the network's preference for the hub.

Random networks are usually simple. Cluster networks can become very complicated. Scale-free networks can prompt complex adaptive behaviors that are less linear, less predictable, and tend toward more extreme outcomes than the other two types.

My grandpa grew up in a commercial context characterized by more persistent and increasingly large clusters. He was effective leveraging these clusters to serve his customers and differentiate his stores from other stores. He even created his own cluster of small stores. But by the mid-to-late 1950s even rural clusters were evolving into scale-free networks. My dad had not yet mastered the lessons. As a result, the younger man was more open to learning the novel lessons of scale-free networks and complex adaptive systems. According to the once-upon Interstate Commerce Commission, in 1932 73.9 percent of ton-miles transported in the United States were carried by "steam railroads". Another 9.4 percent was transported by inter-city trucks. The remaining 16.7 percent was distributed by inland waterways, pipelines, "electric railways", and airplanes.

According to the US Department of Transportation, nine decades later these percentages have been nearly reversed. This transformation has had many sources. Development of the Interstate highway system between 1956 and 1990 was especially important. Deregulation of the trucking industry in 1980 was too.

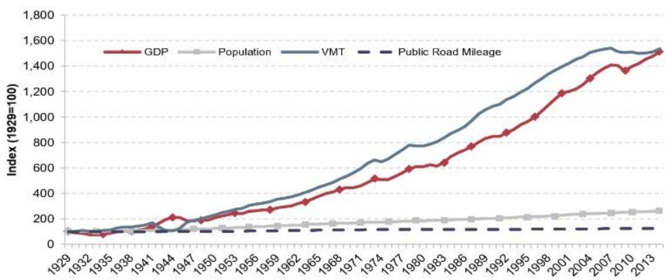


Related to both of those factors, even motivating each, was the explosive economic growth of the United States following World War II. Between 1950 and 1966 the real GDP of the United States doubled. It doubled again by 1988 and yet again by 2016. The rate of increase was even a bit higher on a per capita basis. As demonstrated on the chart below.

After 1929 road miles in the US road increased from roughly 3.3 million to just above 4.1 million miles or about one-fifth (see chart below). The vehicle *capacity* of these roads expanded at a faster rate, but not miles transited. National population more than doubled. GDP multiplied by over 15. Vehicle Miles Traveled tracked GDP. The National Academies of Sciences, Engineering, and Medicine explains,

> A large and extensive road system was already in place in the United States when cars became a major mode of transportation in the early twentieth century. The pattern of the system mirrored land uses and transportation corridors of the nineteenth century. Roads were narrow, primarily composed of dirt and gravel, and for the most part, followed existing topography. Before 1900, only 4% of the roads were paved, leading to poor and unreliable traveling conditions. Yet this system formed the template for the current system. Indeed, the road system has less than doubled in length since 1900.

US Public Road Mileage, Vehicle Miles Traveled, Population, and GDP



Most contemporary high volume, high velocity supply chains increasingly behave as complex adaptive systems. More people with greater buying power generate much increased demand diversity. More frequent and varied "pulls" require more frequent and agile "push". The system increasingly self-organizes around persistent characteristics that shape outcomes but resist sure prediction.

Supply Chains and other networks become complex adaptive systems as they demonstrate the following characteristics:

- **Large Number of Elements**: The abundance of elements and interactions among elements is such that conventional descriptions are not only impractical but cease to assist in understanding the system. Each Walmart store sells about 140,000 Stock Keeping Units (SKUs) – distinct inventory elements. Online Walmart sells 400 million SKUs.
- **Beginnings matter:** Each complex adaptive system has a history. Each system evolves and prior experience influences present behavior. Walmart now has an international footprint. The firm was founded, and is headquartered, in Bentonville, Arkansas. Walmart stores remain physically less prominent in urban areas and typically serve a comparatively smaller market segment in the most densely populated places.
- **Mostly proximate interactions**: Inbound flows depend primarily on a sparse number of comparatively nearby connections. Roughly 80 percent of SKUs sold by Walmart

arrive at a store in Walmart trucks from one proximate Walmart Distribution Center (or occasionally two). Most Walmart customers travel less than ten miles. Surveys have found that more than 90 percent of all US consumers travel twenty-minutes or less for the vast majority of their "everyday" shopping. Over eighty percent travel less than fifteen minutes.

- **Rich Interactivity**: Any element or sub-system is affected by and affects several other elements or sub-systems. In its 2022 Annual Report, Walmart warns, "Given the number of individual transactions we have each year, it is crucial that we maintain uninterrupted operation of our business-critical information systems. Our information systems are subject to damage or interruption from power outages, computer and telecommunications failures, computer viruses, worms, other malicious computer programs, denial-of-service attacks, security incidents and breaches (through cyberattacks, which may be from cybercriminals or sophisticated state sponsored threat actors), catastrophic events such as fires, major or extended winter storms, tornadoes, earthquakes and hurricanes, usage errors by our associates or contractors, civil or political unrest, or armed hostilities."
- **Non-linear interactivity**: Small changes in inputs, physical interactions or other relationships can prompt significant changes in output. The *Ever Given* is certainly a large ship, but miniscule in terms of full global flows. Yet the ship's brief mishap in the Suez Canal had significant amplified network effects. In 2023 Walmart completed its First

Quarter with heavy excess inventory. Over the second quarter it instituted a series of mark-downs and related measures. By the close of the next quarter Walmart was able to report, "net cash provided by operating activities was $18.2 billion for the six months ended July 31, 2023, which represents an increase of $9.0 billion when compared to the same period in the prior year. The increase is primarily due to moderated levels of inventory purchases and timing of certain payments." Scale-free networks are susceptible to dramatic butterfly effects: good and bad.

- **Recurrent Feedback**: Any interaction can feedback onto itself directly or after intervening stages. In supply chains different perceptions of feedback at different tiers of the supply chain can produce what is called a "bull whip effect". In response to pandemic-related supply chain uncertainty many enterprises, including Walmart, ordered earlier and often much more. A few months later empty shelves were full, replaced by stuffed warehouses of unsold merchandise.
- **Indefinite Boundaries**: Systems are open, constantly fluctuating, and it can be difficult or impossible to define system boundaries. *Food Logistics* has explained, "the food chain is becoming progressively more globalized for most countries around the world. This globalization has created a range of opportunities and risks… A far reaching and more complex supply chain is prone to risks brought about by regulatory and non-tariff barriers, disruptions due to natural disaster, political upheaval and economic

instability, rising oil prices and its effect on food production and transportation, and the dynamic and unrelenting variations in consumer demands and desires." From Bentonville, Arkansas Walmart operates over 10,000 stores in nineteen nations beyond the United States.

- **Constant Disequilibrium**: Complex systems do not achieve equilibrium conditions. There is a constant flow of energy that maintains the system's organization. Here's how Kroger has described the complex adaptive systems it shares with Walmart, Aldi, Costco, Amazon, Wegmans, and others: "The operating environment for the food retailing industry continues to be characterized by intense price competition, aggressive expansion, increasing fragmentation of retail and online formats, entry of non-traditional competitors and market consolidation... We could also encounter unforeseen transaction and integration-related costs or other circumstances such as unforeseen liabilities or other issues. Many of these potential circumstances are outside of our control and any of them could result in increased costs, decreased revenue, decreased synergies and the diversion of management time and attention. If we are unable to achieve our objectives within the anticipated time frame, or at all, the expected benefits may not be realized fully or at all, or may take longer to realize than expected, which could have an adverse effect on our business, financial condition and results of operations, or cash flows."

In a single lifetime – say,1950 to current – ancient modes and methods of supply have been mostly replaced or fundamentally altered. There has been an exponential increase in demand. This extraordinary surge in pull – and unprecedented ability to organize around pull – has transformed what and how much is being pushed and how it is being pushed. Many mostly small clusters of local commercial activity have been replaced or are now dependent on very large distant hubs consolidating flows from even farther away. Rivers, ancient ocean shipping routes, and equally old paths and roads now carry daily volumes that often exceed what was carried in a year not so long ago. Much more is produced, much more in moved. Both demand and supply can be intensely concentrated. This is an extraordinary achievement – the stuff of science-fiction – that plays out day-in and day-out without much outside notice.

Proto-Graphs and Network Thinking

There are farms, some near, some far. There are grain mills and bakeries, slaughterhouses and meat markets, canning factories, diners, delis, fast food drive-throughs, five-star restaurants and much, much more. There are farmers markets, bodegas, convenience stores, supermarkets, "club" store, and home deliveries. There are people with more and less purchasing power. There are places where people are crowded and places where people are sparse. There are waterways, roads, bridges, air routes, digital transaction systems, and even more connections, links, thick and thin edges spider-webbing in-between. There are intersections, fuel depots, truck stops, distribution centers, banks, credit card transaction vendors, and more and more vital vertices.

Each person and place is unique. Needs vary. Wants are even more diverse. Value received or delivered in exchange for flow – *potentially* mutually recognized – can be volatile. Distance is difficult. Density matters. Demography is destiny. Hurricanes, droughts, floods, earthquakes, plagues, wars, and more erupt. It is complicated, complex, and quite often chaotic—in the most rigorous meaning of each term.

Faced with dynamic flows that exceed direct observation or confident understanding, I impose abstractions. I accept complexity and its attendant uncertainty while trying to engage superabundant reality with cognitive tools that reduce the torrent to something I can consume and convert to practical insights and (potentially constructive) interventions. So, within the constant chaos I find (create?) nodes and links, agents and actors, capacity concentrations, bottlenecks (sometimes becoming chokepoints), demand and supply, push and pull. There is flow… or sometimes not.

As already noted, I start by looking for physical concentrations of volume or potential volume. For example, Safeway is the grocery market leader in the San Francisco Bay Area. The Safeway (Albertsons) Distribution Center is about sixty miles east of San Francisco's city hall (see satellite image below). Just by itself this DC is the source for about a quarter of food-at-home flows for almost eight million people in the Bay Area. Not surprisingly, immediately proximate to this DC are similar facilities for Amazon, Costco, Owens & Minor (medical goods), and more. Very Important Place.

Distribution Centers near Tracy, California

The grocery distribution centers serving Safeway's three largest direct competitors are also close by. Precise data on grocery flows are difficult to generate. But both published sources and private conversations indicate the following proportions were roughly accurate for the San Francisco Bay area early in the 2020-2023 pandemic.

- Albertsons (Safeway): 24 to 26 percent of grocery flows (from west of Tracy on the map)
- Super Store Industries: 21 to 23 percent (Manteca)
- C&S Wholesale Grocers: 11 to 13 percent (north of French Camp)
- UNFI (Supervalu): 11 to 13 percent (Stockton)

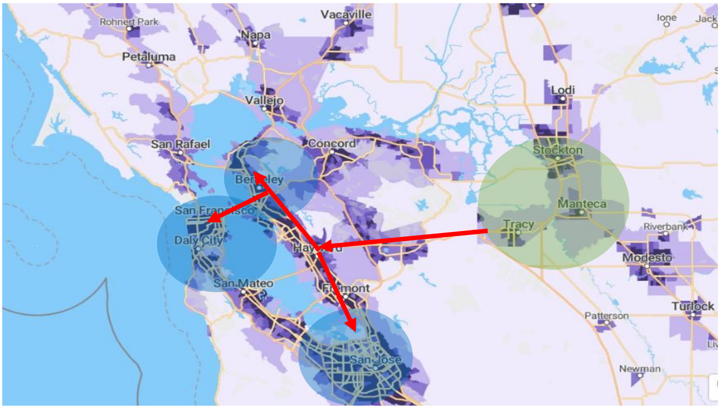
These four nodes alone constitute more than sixty percent and potentially up to three-quarters of food volume serving this region's grocery sector. Finding this sort of proportional concentration along a twenty-mile edge of a major metro area is not unusual.

Given the proportion of total volumes being discharged from this comparatively small area, it is also not surprising to find near-by high proportion transportation links. Interstate 580 between Tracy and Dublin is the local version of the Suez Canal. On most days it is a high velocity channel for efficiently, affordably pushing high volumes toward high velocity pull. On bad days it is a chokepoint. There are alternatives, but all add distance and duration (and costs), thereby delaying discharge to demand. Everyday there some delays. The intersection of the I-580 with US-101 and then across the Bay Bridge is notorious. With the seismic fault lines running beneath this channel and its alternatives, it is not difficult to imagine a chokepoint emerging between supply and demand much more consequential than the *Ever Given's* disruption of global maritime flows.

Math oriented readers may recognize a familiar analytical framework emerging: There are volumes moving in specific directions, so we have velocity, also-known-as the First Derivative of calculus. There is also acceleration or deacceleration of velocity, the Second Derivative. Is it getting worse or getting better? When flows slow it can be especially helpful to calculate the Third Derivative (also-known-as jerk): what is (de)acceleration's rate of change? How quickly is it getting better or worse? In the worst cases answers will always be rough estimates much more than precise measures. But especially in a crisis this abstract big-picture perspective for diagnosing root problems and recognizing systemic options can help to discern *possible* signals amid mind-numbing noise.

I usually focus on two kinds of concentration in relationship: I try to find and frame *concentrated demand capacity,* for example dense populations in San Francisco, Santa Clara, and Contra-Costa counties. Each of these places (and others near-by) have a similar dependence on *concentrated supply capacity* in San Jonquin County. Each of these concentrations actually consist of thousands to millions of largely independent consumers and suppliers. I find the alleged concentrations through cognitive abstraction. These concentrations are connected in many ways, but – as outlined above – I also tend to focus on high-volume truck flows moving on a small set of routes. So, my personal mind-map starts with population density (map layer below) showing major demand nodes (blue circles) connected to the major supply nodes with the highest capacity links (red lines). In this case I treat the Tracy-to-Stockton concentration of supply capacity as one node (green circle). Are you intrigued or horrified?

This radical distillation (or reconceptualization) of reality can be characterized as a primitive graph. In mathematics Graph Theory helps model reality by using nodes (points or vertices) connected by links (lines or edges). Just as a map abstracts terrain and the built environment to distill geographic reality, graphs abstract relationships and interactions (or potential interactions) across space and time. With sufficient – often tightly guarded proprietary information – the first tier of enterprise-specific supply chains can be minutely graphed to measure flow.



Network Concentration, Percolation, and Punctuation

I very seldom have access to such rich supply chain data even for a single enterprise. It is still unusual for individual firms to have this sort of detail, especially for anything beyond direct suppliers and consumers. According to several surveys fewer than one-fifth of major companies have the data-analytics and operational capability to visualize recent real-time internal flows. I have never had access to this depth of detail for any set of top competitors serving the same large population.

I want to be – claim to be – an empiricist. I gather evidence to confirm, clarify, or deny my impressions. I want to test what I sense against credible data and what others sense. Yet I do not claim to be a scientist. There is, for me, too often a troublesome reductionist, materialist, quantitative bias to how the scientific method is applied, especially to messy socio-technical systems such as a supply chains. I have also encountered too many so-called decision-makers who depend too much on retrospective data when trying to shape the future. Too often too little too late. Such decisions can seldom wait for certainty.

I am much more a humanist. I admire the rigor of science. I try to apply scientific principles and processes. But while I want to be informed by science, I am also prepared to risk the gestalt of experienced self-critical strategic choice. Data quality, access, integration, and synthesis may yet displace this bias – but not yet. Using whatever data are available, nascent principles of Network Science, and my best guesses I try to find meaningful fulcrums and effective levers to move the world.

Concentration

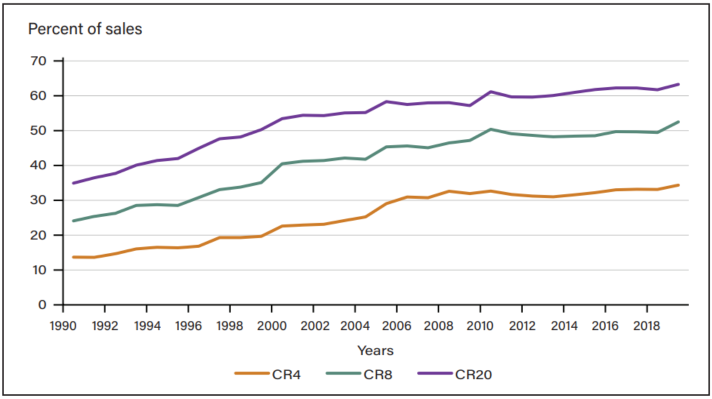
Supply chain concentration is mostly an emergent – often rational – response to decades-long demographic, economic, and commercial challenges. Capacity concentration has often improved the efficiency and effectiveness of production, distribution, availability, and costs. There have been profoundly utilitarian – if sometimes Darwinian – benefits. There have been plenty of negative consequences for particular places and people. In any case, concentration can be a useful fulcrum.

The more capacity concentrated in any single place and/or function, the more a whole system is at risk if that concentration is disrupted. The *Ever Given* is one of the largest ships that has ever sailed. But if the *Ever Given* had sunk and its whole cargo lost somewhere at sea, the systemic impact would probably have been limited to marginal increases in maritime insurance rates. Because, instead, the ship wedged itself across one of the most concentrated flows on the planet the systemic impacts were significant and extended. The loss of any one of the four grocery distribution centers mapped on page 22 would be difficult. The long-term loss of Interstate-580 would be worse. No fulcrum, no leverage, no movement.

Network Science has identified so-called Giant Components – aka Strongly Connected Components or Largest Connected Components or sometimes just Big Components – as a recurring characteristic of scale-free networks. Giant Components encompass a disproportionate share of all nodes and, as a result, the links between these nodes. The level of grocery market concentration outlined for the San Francisco Bay Area is not unusual—and is less extreme than in many other places in the United States.

According to a US Department of Agriculture study of the grocery retail sector, "market concentration has steadily increased between 1990 and 2019… Most of the growth has been due to the increased market presence of national and regional retailers and results show that [one measure of national-level concentration] has increased more than 458 percent compared to 94 percent at the county level."

National Concentration Ratios for Top 4, Top 8, and Top 20 Retailers (1990-2019)



Notes: CR4 = top 4; CR8 = top 8; CR20 = top 20. Food sales are estimated based on the sales per employee ratio calculated by the number of employees and the North American Industry Classification System (NAICS) code. NAICS included: 445110 (supermarkets and other grocery, except convenience) stores) and 452311 (warehouse clubs and supercenters). Food sales are calculated using the U.S Bureau of the Census' Economic Census product lines statistics on the percentage of sales of food.

Source: USDA, Economic Research Service, using data from the National Establishment Time Series (NETS).

There is evidence that many networks are predisposed to concentration. In the case of scale-free networks, it is common for 80 percent of links to be associated with only 20 percent of nodes. This is sometimes called a Pareto Distribution or Pareto Proportion referencing the 19th Century Italian who first noted the pattern. Pareto found that there is a recurring tendency for a small portion of any distributed set to generate disproportionally high outputs for the whole set. Roughly four-fifths of Pareto's peas came from barely one-fifth percent of his pea plants.

It is often possible to identify a small number of sources or carriers (or routes) or consumer characteristics for a Pareto Proportion of demand and/or supply. One-fifth of all

US grocery distributors are responsible for over four-fifths of grocery distribution. Only three US pharmaceutical distributors are responsible for more than three-quarters of pharmaceutical flows. Only three US maritime ports handle more container volume than all the rest combined. There have recently been more or less 145 petroleum refineries in the United States. Total US refining capacity is just about 18 million barrels per day. The six largest refineries, producing about one-fifth of total US refined products, are all in the northwest corner of the Gulf of Mexico between Galveston Bay and Baton Rouge, less than 250 miles as the hurricane flies. Just three percent of US counties account for over half of national Gross Domestic Product.

When these remarkably robust capacity concentrations are operating as intended or when they prove to be resilient in a crisis, flows for the entire supply chain – all the other related nodes and links – will be supported, potentially enhanced, and probably expedited. But serious disruptions directly impacting these dense concentrations can have staggering impacts on system capabilities near and far.

Percolation

Many aspects of supply chain concentration generate systemic benefits—until Giant Components pool too much system-wide risk. "Too much" usually reflects especially *dense connections between* nodes within the Giant Component. The more percolated a network, the more link density, the more saturated any network: the higher potential network velocity. The more percolated a network, the faster pull signals can distribute wealth across that network and attract push. The more percolated a network the faster interdependent failures multiply and cascade across the network. Contagion can be good or bad.

For example, a recent study found, “The supply chain of medical equipment includes a relatively small number of extremely well-connected nodes and hence exhibits a highly skewed degree distribution (link patterns). This characteristic makes this supply chain particularly robust to random disruptions, as the probability of failure in small well-connected firms is relatively lower. However, the same characteristic makes the supply chain highly vulnerable to intelligent attacks due to the high impact of targeted attacks launched on the small number of the well-connected firms.” (Lavassani et al)

The authors of this medical equipment study note, “Supply chain failures are usually caused by random events (such as natural disasters, including pandemics) or targeted/strategic events (such as trade wars, terrorism, sanctions, trade regulations, and competitive pressures). Percolation theory provides analytical tools to explore both types of causes of interruption. The study of targeted attacks can also reveal firms’ strategic supply chain weaknesses and strengths.”

My grandparents owned Mirro-Matic Coffee Percolators. Ground coffee beans were measured into the reusable metal basket filter just below the lid. Boiling water continuously pushed up a metal tube to spray over the grounds. Percolation was signaled by a distinctive gurgling sound and bubbling into the hollow glass crown as boiling water discharged from the tube spreading through the coffee. Grandma Palin precisely timed percolation for each person. My children's coffee (mostly cream and sugar) was poured moments after the first few perks. She poured her own cup perhaps one minute later. Grandpa's two or more cups of coffee – each progressively stronger – came after several more cycles. Each cycle increased saturation and related extraction. Excessive saturation and heat eventually produce an unpleasant brew.

Percolation is good. The "best" amount of percolation can vary by purpose or preference. But eventually too much percolation is bad for everyone—even the pot.

In several contemporary commercial sectors there is increasing evidence that – unlike grandma – we have neglected the accumulated saturation and extraction of network percolation. Output is susceptible to recurring interruptions or even total loss in a sudden fire.

Punctuation

Percolation tends toward concentration. Over-percolation results in over-concentration. Over-concentration can set the stage for dramatic punctuation: many insistent question marks and several scary exclamation marks.

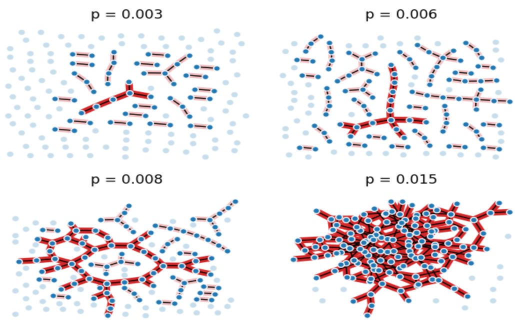
In January 2020 several weeks before the World Health Organization determined the novel coronavirus qualified as a pandemic, I sent around several notes, including the following excerpt. Percolation is implied. Concentration is explicit.

> US healthcare sources consistently report that the United States is dependent on Chinese manufacture of "medical consumables" (all FDA Class I products and some Class II products) ... China dominates low-cost medtech manufacturing with up to 78 percent of world capacity at the low-end. This includes products such as sanitary gloves, disposable syringes, gauze, serum collection tubes, etc. In recent years, China’s export market share for medical gloves to the US is about 30 percent. It is estimated that 97 percent of non-medical disposable gloves used in the United States are sourced from China.

> Lower end medical goods manufacturing and logistics -- especially for domestic consumption -- is widely distributed across China. But export-oriented industries in China tend to be geographically clustered. Financial flows seem to suggest that the medical device sector is concentrated in Guangdong Province (Southeast, near Hong Kong) and in Shanghai with its adjacent Jiangsu province. Companies in these locations account for three-quarters of Foreign Direct Investment in Chinese medtech. Medtech companies clustered in Beijing and Shandong provinces are important to the domestic market but have not attracted the same level of Foreign Direct Investment.
>
> Shandong is the biggest medical material and supply manufacturing province in China, accounting for more than a third of industry revenue. Shandong, Jiangsu, Zhejiang and Guangdong are all coastal provinces, accommodating 60 percent of medtech enterprises Firms in Shandong and Guangdong tend to be larger, while Jiangsu and Zhejiang are smaller. Henan is an inland province, with a large population and well-established transportation system… The aggregation of similar enterprises in has led to regional economic advantages which appear to rely on the Yellow River network.

The emergence of China's medtech Giant Component (sometimes plural) was intentional, gradual, and in terms of cost-price optimization entirely reasonable. An initial cost advantage attracted more pull from more links (percolation). As sales volumes grew so did economies of scale, supporting even more price-per-unit comparative advantage. Eventually these lower cost demand-links thickened while links to higher cost nodes thinned. Non-China nodes experienced declining pull, flows evaporated, and desiccated nodes disappeared. Meanwhile pulls on the Yellow River nodes increased, links proliferated, nodes consolidated, combined, and thrived. This concentration was not limited to sourcing, push-capacity from East China also blossomed, carrier capacity to the rest world flowered. But distance persisted, along with all the potential surprises that *Ever Given's* troubles exemplify.

From a network perspective, as percolation continues more pulls converge on fewer, more fully saturated nodes, denser links pull on larger nodes. More push emerges from fewer but bigger channels. On many network maps both links and nodes get bigger and darker. The pandemic's "attack" on low-cost medtech Giant Components was not "intelligent" nor intentional. The pandemic's spread was random (even if accelerated by non-random human structures and systems). But concentrations percolated over the last generation had become, in any case, fat targets—intentional or not.



The pandemic pincered these targets: First, with labor and transport disruptions reducing sector-wide supply-push capacity and, second, by skyrocketing demand-pull far exceeding pre-pandemic push capacity.

The pandemic dramatically unveiled many previously seldom-recognized Giant Components that thirty years of persistent percolation created: Fewer ports handle bigger ships and much larger proportions of total flow. Just twenty global ports account for roughly 40 percent of total container throughput. About sixty percent of seventy-some-million US hogs are slaughtered at only fifteen enormous processing facilities. In 1976 the top four pork processors delivered about one-third of pork output, by 2018 that proportion had more than doubled. Before the pandemic the top five global semiconductor manufacturers produced one-third of outputs. The top twenty-five manufacturers produced two-thirds of all semiconductors. Many more Giant Components live-large yet avoid notice and are neglected.

The pandemic revealed these concentrations but did not cause these problems. Causes are embedded in systemic structures and behaviors of high volume, high velocity, networks of high-capacity nodes and densely connected links that have rapidly developed to effectively deliver supply to rapidly growing demand. In his 2014 *Book of Extremes: Why the 21st Century isn't Like the 20th Century* the pioneering network scientist Ted G. Lewis offers this summary:

> The modern world differs from previous generations mainly due to vast network connections that replace independent random events with highly dependent conditional events. The 21st century is an age of lop-sided long-tailed probability distributions rather than the classical Normal distribution. Like episodic waves striking the beach modern day events come and go in bursts—most are clustered together in time and space, but occasional bursts are separated in time, space, and consequence. This model of reality is called punctuated reality, because of the wave-like behavior of the complex systems found everywhere in modern life.

Punctuation is an inevitable outcome of persisting percolation. Grandma loved her percolator, but she knew when and how to unplug it. Too much density delivers a sodden, soupy, bitter brew.

People and our Perceptions

Using different words and concepts, Grandpa Palin recognized the risks emerging from over-heated percolation. He tried to resist. My dad perceived resistance was futile, but he hoped it might be possible to ride the waves.

Both my dad and his dad understood that Americans were more mobile. Roads were better. Personal automobiles and gas were affordable. Many had more disposable income. It was much easier in 1955 than in 1935 to shop around for price, variety, service, and personal convenience. The more personalized service of many small local stores could not always compete on price or variety. The velocity of demand-pull significantly increased after the end of World War II. Not every storeowner could run fast enough.

On a slightly different scale the mid-Twentieth Century US grocery sector experienced shifting flows similar to those of early Twenty-first Century low-cost medtech. Well-assured, low-cost transportation combined with cost/price product advantages attracted customers to new, bigger, more distant sources.

The proportion of US household income spent on groceries fell from about one-quarter to one-tenth between 1935 and 2018. Prior to 1950 most US grocery stores were under 10,000 square feet. All of grandpa's stores were well-under that threshold. By 1960 the average grocery store – now a supermarket – was about 20,000 square feet. By 2010 40,000-plus square foot stores – or grocery departments in so-called supercenters – were common. Dad's stores expanded with this trend. Despite significant gains in population and wealth, since 1990 the number of US grocery stores per capita has fallen by about one-third[2] even as overall sales have increased.

Is this pace of change steady or sharp? Is a lifetime's scope short or long? Is quantity measured over time consistent, growing, or falling? Is the quantity's rate of change over time

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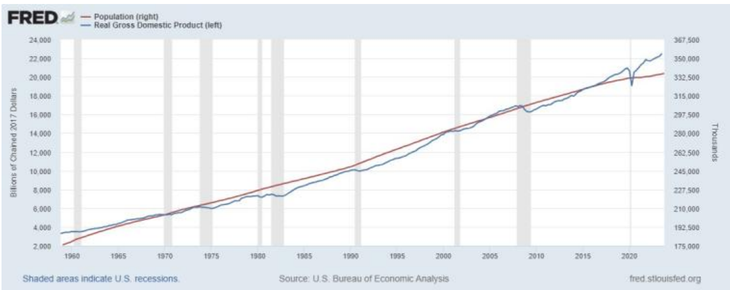
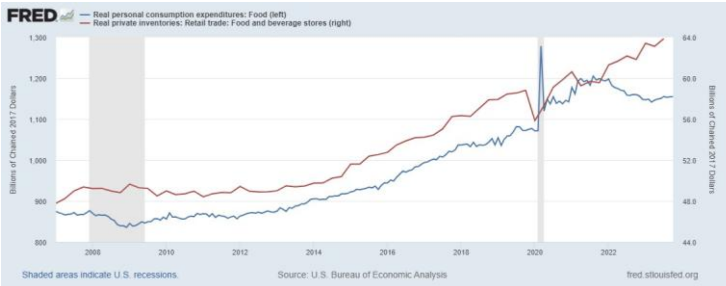
[2] Grocery store numbers are tough to track. Are convenience stores grocery stores? Are Costco Warehouses grocery stores? NAICS 4451 is about the best category count we've got. According to the Census Bureau in 2017 there were 56,063 convenience stores, aka grocery establishments. There were 86,884 supermarkets and other. Costcos were not counted in the "other" category.

speeding or slowing? What is real? What is each person's experience of reality? What meaning do we derive from these perceptions? Answers valid in a global or national context can be dramatically different for specific regions or localities. The rate of change in (de)acceleration will be different depending on the timeframe applied. What do you perceive in the relationship between US population and real Gross Domestic Product (GDP) shown on the chart immediately below?



What do you perceive in this next chart showing food sales (*not* inflation-adjusted) and population? Are there meaningful connections between the prior chart and this chart? What additional information do you want? How would you like to view the information: charts, tables, narratives… what?

How about this third chart? The blue line is dollars spent on food-at-home – mostly grocery consumption. The red line is the dollar value of food inventories. Each factor is inflation-adjusted. How are the slopes of these two factors related? What do divergent slopes imply?



These three charts report national outcomes. A 2017 study by the US Department of Agriculture suggests how local conditions can differ from overall conditions:

> From 2005 to 2015, the total number of grocery stores across the 48 contiguous States and the District of Columbia increased by 7 percent (from 47,000 to 51,000), while the population increased by 8.5 percent (from 294 million to 319 million) ... Although the total number of food retailers in the United States increased over the last decade, there was significant county-level variation. The total number of food retailers declined in 969 counties (31 percent), among which 30 counties (1 percent of all counties) had a decrease of more than 5 stores. In contrast, food retailers increased in 1,146 counties (37 percent); 211 counties (7 percent) had an increase of more than 5 stores.

> On average, urban counties had an increase in the total number of grocery stores, particularly small-format stores. On average, rural counties had an increase in small-format stores but a decrease in large-format stores.

If you are employed in the food business, you may recognize some personal relevance in these data. But all this is plenty distant from most of our daily priorities. Even a grocery professional may be more *interested*, than really care. If you are a supply chain professional, you may acknowledge that you *should* be interested, but relevance seems a bit elusive. There is plenty to do every day just to move your inventory to your consumers. A state governor might listen politely and ask a couple of good questions but need to move on and quickly forget. The governor's chief-of-staff will probably be less patient, less polite, and keep the governor moving. A corporate CEO or CFO either knows these details (and much more) cold or is clueless, depending on the corporation's competitive priorities and the personalities of these senior decision-makers.

I have shown these same sorts of charts to many city, county, tribal, state, federal, and international emergency managers. Uptake is variable. The inputs and outputs are usually perceived as relevant to emergency management missions but outside their authority or ability to engage. Emergency managers are interested, but don't really care that much about how millions are fed every day. Emergency management leaders are more interested in what these data may say about how millions will *not* be fed on a very bad day. But then, once they understand the orders-of-magnitude involved, most emergency managers decide the issues are "above my paygrade."

Most of us care most about what we need to do today and most days. Frequently recurring daily challenges are where we focus most of our attention. A realistic – even humble – sense of span-of-control is usually helpful. But cognitive dissonance, even anxiety, is appropriate when there is credible and accumulating evidence of significant risk to this status quo. Active adaptation to emerging reality – even if uncertain – is also helpful. Uncertainty need not cause paralysis. Uncertainty rewards wisdom.

What I perceive in the charts immediately above and in prior pages is an enormous system that in the last century – and especially in the last thirty years – has achieved unprecedented, barely conceivable, concentration and related capacity. Our Giant Components are huge, hugely capable, and this huge capacity is fundamental to fulfilling a whole host of essential human needs. Because of this achievement we are at risk when any Giant Component is seriously compromised.

Precisely because of the scope, scale, and related complexity of the high-capacity systems on which contemporary societies depend, individuals can be dissuaded from cutting through constant noise to give meaningful, regular attention to something that by-definition is outside their control—even if it is within their influence.

Over time most of us learn that personal and professional effectiveness typically unfolds from when, where, and why we decide to consistently invest our energies. From time to time many of us mutter to ourselves some version of *grant me the serenity to accept the things I cannot change, the courage to change the things I can, and the wisdom to know the difference.*

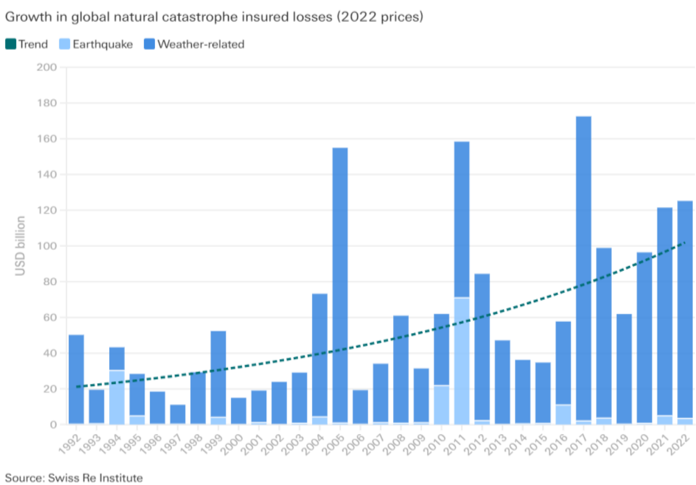
Wrangling that wisdom is not easy – and never guaranteed.

Concentrations, Climate Change, Viral Cascades, and Catastrophes

According to the insurance company Swiss Re, insured losses increasingly accrue from a relatively few especially hard hits, "Between 2013-2022, there were on average 70 low severity events each year, yet their contribution to total insured losses was just USD 11.7 billion. During this same period, an average of just two high-severity events each year contributed USD 34.4 billion cumulatively to total losses. Value concentration due to economic development, urbanisation and growing populations – often in regions susceptible to natural hazards such as coastal regions or river fronts – are the main physical drivers of associated losses."

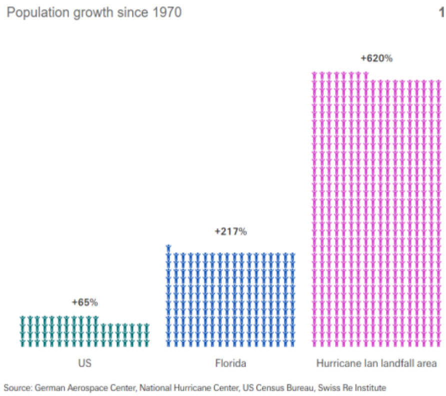
Some will look at the chart below and perceive two parallel realities: First, there is a persistent, reasonably predictable series of low severity insured losses across time. Second, there is an occasional burst of a much harder-hitting event. Rather than random one-offs, these high waves are a core characteristic of networks that feature densely linked Giant Components. As economic development, urbanization, growing populations, demand velocity, and socio-technical abilities to fulfill demand-pull accelerate, Giant Components proliferate and intensify. Higher waves are more frequently spawned.

Network scientist Ted G. Lewis explains, “Bursts aren’t isolated events that affect just a few people, places, and things. They are part of constantly propagating chain reactions circling the globe. Like hundreds of domino chains collapsing all at once, waves, cars, power plants, power blackouts, terrorist attacks, airplane crashes, and Internet exploits are simultaneously and constantly spreading waves of large and small incidents.” These global chain reactions reflect a tightly connected, even accelerating reality of periodic punctuation.



Swiss Re labels Hurricane Ian a “high severity” event:

> Looking at the numbers, the 2022 North Atlantic hurricane season was relatively benign. There were 14 named storms, in line with the 14.4 annual average from 1991-2020. Insurance-relevant storm activity was below forecast with just two major hurricanes of category 3 or higher, below the historical annual average of 3.2 major storms. Yet the 2022 season was the third costliest on *sigma* records because of one storm: Hurricane Ian. Resulting in estimated insured losses of USD 50-65 billion, Ian demonstrated that the main driver of losses is a hurricane's landfall location. Ian made landfall in western Florida in late September as a category 4 storm and hit an area that had seen rapid population growth, an increase in built areas and accumulation of physical assets. Since 1970, the population of the Ian-struck area in the Cape Coral-Fort Meyers metro area has increased by 620%, more than the population growth in the state of Florida at +217% and the entire US at +65%.



Hurricane Ian's September 28 Florida landfall could easily have had even worse consequences. Population is not the only attribute of Giant Components. I was supporting FEMA's preparations. Before dawn on Wednesday, September 27 I wrote:

> Given recent assessments by the NHC [National Hurricane Center], Hurricane Ian now poses a significant threat to the Port of Tampa due to storm surge. It will not be possible to gap-fill an extended loss of Tampa Bay fuel infrastructure. As the hub for Central Florida's fuel supply, the cascading effects on critical supplies (most freight arrives in Florida by truck), evacuation efforts, and temporary power generation (mostly diesel powered) could combine to be catastrophic.

A direct hard hit on Tampa's port infrastructure and related pipelines has been a recurring worst case worry over successive hurricane seasons. Fortunately for those dependent on the Giant Component centered at Tampa, a last-minute southeast jog took Ian south of earlier NHC forecasts. As the Swiss Re report makes clear, the devastating and deadly hit on the Cape Coral-Fort Myers metro area suggests the sort of explosive damage Tampa barely avoided. In early October 2022 here is how I reviewed the strategic implications:

> Hurricanes always involve a potentially deadly dance with uncertainty. Each forecast track is a rough probability. The same force interacting with different topographies at

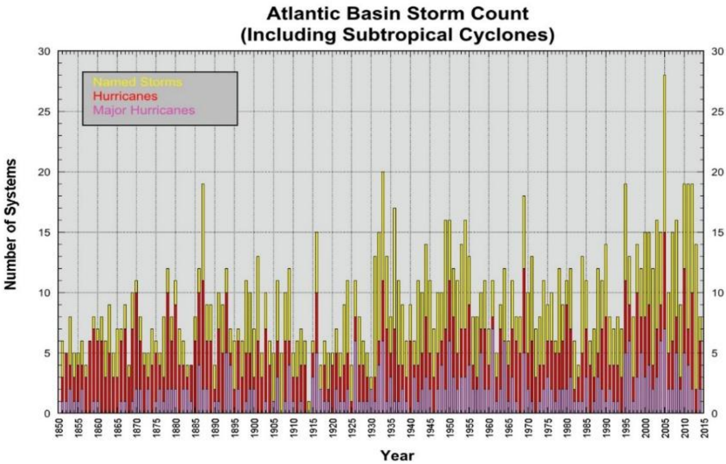
different angles can generate dramatically different storm surge. A ten-mile difference in track, and whether a target is left or right of track, can cause very different consequences in terms of lives lost and supply chain capacity destroyed (or spared).

For most of two days before landfall in the United States, Hurricane Ian threatened to hit the heart of the system that delivers fuel and food to millions across much of Florida. A night-before swerve mostly averted this heart. But the body blow taken elsewhere killed too many, destroyed more than 5000 homes, and signals how hard it would have been for the heart to have survived a direct hit.

Contemporary demand and supply networks tend to concentrate capacity to move greater volumes at greater velocity and less cost. There are many benefits of concentration. But the same tendencies inevitably pool risk. Hurricane Ian's close encounter with the Tampa-to-Orlando supply chain cluster – and its still tough impact on several crucial nodes and links elsewhere – clarifies the strategic risk involved. Ian's dance has also revealed the absence of any credible current capability to meaningfully mitigate this worst-case risk.

More quickly intensifying hurricanes and more extreme hurricanes are expected by many climatologists, as the historical record also seems to suggest (please see chart below). The number of hurricanes that strengthen from

Category 1 (or weaker) into Category 3 (or worse) within 36 hours has more than doubled in this century. Based on anticipated climate patterns, globally there may be slightly fewer Tropical Cyclones but taken together these hurricanes will deliver one-third greater intensity



NOAA, National Hurricane Center

According to the US National Earthquake Information Center about fifty-five earthquakes per day are now able to be recorded. "According to long-term records (since about 1900), we expect about 16 major earthquakes in any given year. That includes 15 earthquakes in the magnitude 7 range and one earthquake magnitude 8.0 or greater. In the past 40-50 years, our records show that we have exceeded the long-term average number of major earthquakes about a dozen times. The year with the largest total was 2010, with 23 major earthquakes (greater than or equal to magnitude 7.0). In other years the total was well below the annual long-term average of 16 major earthquakes. 1989 only had 6 major earthquakes and 1988 only had 7." Sounds bursty or wave-like to me.

Floods, hurricanes, earthquakes, intense and extended cold, intense and extended drought, wildfires, infrastructure failures and attacks, plague, war, and more threaten demand and supply networks. Some threats deliver sudden hits, others build-up over time. Both slow-onset and recurring threats tend to increase system stress. Sudden shocks can especially threaten already seriously stressed systems.

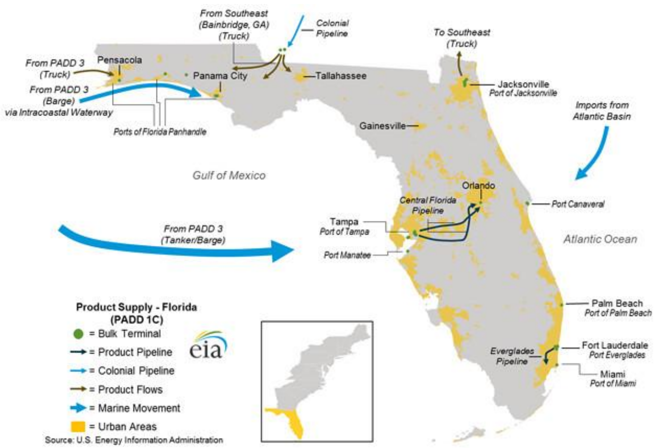
Consequences do, however, differ depending on where the stress or shock is experienced and how many have the experience. Eleven months after Hurricane Ian the equally strong – and late intensifying – Hurricane Idalia made landfall at one of the least populated places on the Florida coast and continued through some of the least populated parts of Georgia. Great strength but low severity.

Above Swiss Re estimated the insured financial losses associated with Hurricane Ian at up to $65 billion. In 2015 Karen Clark & Company concluded that Tampa's insured risk is over $175 billion.

> There are several reasons why Tampa is the most vulnerable US city to storm surge. First, the continental shelf is relatively wide off the west coast of Florida which means the local bathymetry will accentuate the rise in sea surface

from a major hurricane. Second, Tampa Bay creates a large funnel—particularly for a hurricane with its radius of maximum winds near the mouth of the bay. A severe storm with the right track orientation will cause an enormous buildup of water that will become trapped in the bay and inundate large areas of Tampa and St. Petersburg. Fifty percent of the population lives on ground elevations less than ten feet.

Human costs always exceed financial costs. The higher any upstream "costs", the more delayed recovery and deeper downstream costs. Destruction of the grid distribution network is tough. Destruction of the grid transmission network is worse. Long-term, unexpected loss of electric generating capacity will reduce both distribution and transmission capabilities.



Aspects of the Giant Component at Tampa that worry me the most include dependencies along the Interstate-4 Corridor – all the way to Orlando and beyond – that relate to fuel deliveries at the Port of Tampa and pumping fuel through pipelines from Port of Tampa. If the port facilities, including barge offloading facilities and fuel racks, are wrecked by storm surge there is no near-term replacement. If fuel runs out for the grocery cluster at Lakeland and nearby, food flows and other crucial freight will lose velocity even if their volume is untouched. That has implications for at least seven million people – and will eventually impact Miami too.

Each Giant Component is unique. Each demonstrates similar behavior patterns. These include a tendency for cascading flows – good and bad -- across their percolated network.

Preferences Regarding Reality

Demand pulls supply. Supply pushes toward demand. Increasing pull velocity encourages higher push velocity. To increase velocity and control costs supply chains tend toward more concentrated nodes that are more densely linked (percolated). This high-capacity network of demand and supply is robust and resilient – unless an especially high-capacity concentration (Giant Component) experiences serious disruption or destruction (punctuation). The more extensive the time-and-space of any disruption, the more hazardous the human consequences. For the most concentrated sources of demand, this preexisting high-capacity network is the only practical source of life-sustaining critical flows. There are no other realistic sources of near-term sufficient capacity. Catastrophic potential is baked into the core characteristics of our highest capacity networks. Rapid restoration (and sometimes redirection) of this preexisting capacity is fundamental to serving human needs under severe duress.

This seems to be the systemic predisposition of high-capacity flows. As a result, these are the patterns around which I organize my thinking and doing, even when I might prefer otherwise.

Further Reading

A research bibliography of resources referenced above is available starting on page xxx.

The books below provide more information on main topics considered in Preferences.

Network Science by Albert-László Barabási

Predictable Surprises by Max Bazerman and Michael Watkins

Mission Impossible by Lee Clarke

Noise by Daniel Kahneman et al

Bak's Sand Pile by Ted G. Lewis

Book of Extremes by Ted G. Lewis

Rules, Games, and Common-Pool Resources by Elinor Ostrom et al

The Power of Resilience by Yossi Sheffi

How the World Really Works by Vaclav Smil

The Wealth of Nations by Adam Smith

Scale by Geoffrey West

PROBLEMS

A disruption of continuity. An impediment to forward movement. Derived from an ancient Greek term meaning thrown (*ballo*) forward (*pro-*), as a rocky headland rises between our ship and our destination or an enemy force is deployed in front of out intended path. We can directly confront problems or move around problems. In any case, the objective is to complete our original route or adjust our goals as necessary to achieve our purposes.

As scope and scale expand, I perceive reality as predisposed to percolation, concentration, and punctuation. In my experience reality-at-large demonstrates a preferential attachment to these behaviors. Supply chain behaviors are just one prominent example of these predispositions.

Is this accurate? Is there a threshold of scope and scale below which this not accurate? Do percolation, concentration, and punctuation increase in speed and reach as scope and scale expand? If so, when and how does the potential power of punctuation become innately self-destructive? If so, when and how can percolation and concentration enhance network resilience in case of severe punctuations? Is there an Aristotelian mean? If not, what are constructive alternatives? If so, how do we, like Grandma Palin, watch carefully enough to choose the right action at the right time to achieve the best outcome?

My preferences and understanding of reality's preferences have emerged from experience. I have derived operating principles—or at least strategic hypotheses – for engaging novel problems. A key comparative advantage of the human species is our ability to share our experiences. My direct experiences growing up in the grocery business have been indirectly influenced by experiences of network scientists (and many others). I have adapted network science to my experiences. In reading this text you are indirectly accessing my experiences. You may find aspects of my experience adaptable to your experiences.

Following are five of my experiences: five problems that I have engaged.

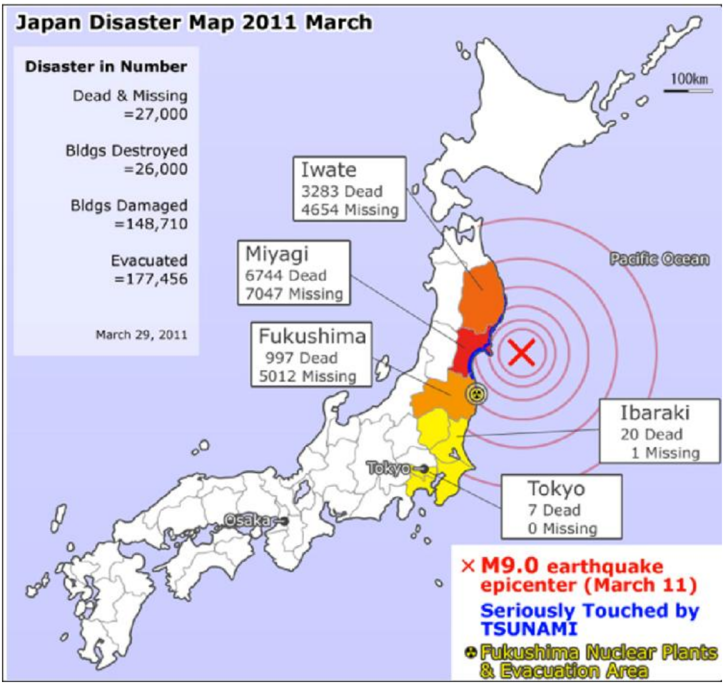
- Three Strikes You're Out (Japan Triple Disaster 2011)
- Misunderstandings Multiplied (Superstorm Sandy 2012)
- Distance, Density, Mistaken Identities (Puerto Rico 2017-2018)
- Demand Disruptions and Eruptions (Pandemic 2020-2022)
- Suddenly One Winter (EU Natural Gas 2022-2023)

My role in each of these elephantine problems was miniscule. Just the touch of a tail or toenail or trunk. Yet I discern broadly applicable principles. It will benefit each of us to review these experiences critically and comprehensively. In conversation with you I may revise meanings I have derived from these experiences. Are you ready to do the same with meaning you have derived from your prior experiences? In any case, here we go – together – on a quick trip around the world and across twelve years.

Natori, Japan post-tsunami

Micro-Case 1: Three Strikes You're Out (Japan Triple Disaster 2011)

On March 11, 2011, a magnitude 9.0 undersea earthquake (strike one) spawned a tsunami (strike two), pulverizing the Northeast coast of Japan and doing damage far inland. The ocean-facing Fukushima Nuclear Power Station was especially hard-hit (strike three). More than 15,000 died. Over 200,000 were left homeless. In the immediate aftermath of the event 4.4 million survivors were without electric power and over 1.5 million lost access to public water systems. A winter storm shortly followed.



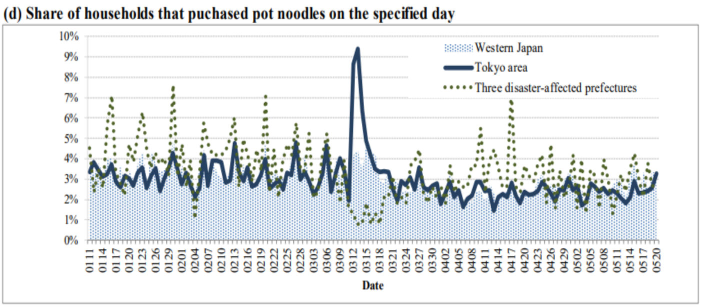
The large impact zone – roughly equivalent to the distance between Los Angeles to San Francisco – is mostly non-urban but encompassed more than nine million persons.

The usual suppliers of food to the hardest hit areas were entirely side-lined for several days. Initially, several roads and bridges required repair. Some delay in regular supply chain operations also resulted from disruptions to fuel supply. The earthquake-related loss of a key refining node reduced Japanese national fuel capacity by roughly one-quarter. The mantra was often heard (in Japanese): "No Roads, No Gasoline, No Delivery."

But even after roads were reopened and fuel was secured, the government excluded commercial capacity from the impact zone. A military and police perimeter was established, inside of which the government attempted to create entirely new supply networks.

Outside the immediate impact zone – especially in Tokyo – the food supply chain was hit hard by hoarding. An analysis of retail pull-signals and inventory records conducted in the two years after the event found, "Although sufficient supplies of food, fuel, and emergency goods to meet demand in normal time were available, store shelves were left empty due to panic buying and hoarding of certain foods and other basic supplies in the wake of the earthquake. Empty shelves, in turn, gave rise to a vicious cycle of consumers scrambling to stockpile such goods." (See chart below)

This is a classic, recurring feature of contemporary demand and supply networks. When and where demand-pull surprisingly spikes there is almost always plenty of upstream supply. Regional buffer stocks for most food and fuel products are usually sufficient for several days or even weeks of "ordinary" demand. But distance between distribution centers or fuel racks and retail outlets remains the same. The number of truckers and trucks remain the same (or less, depending on the cause for the demand spike). So, while the volume needed to fulfill demand is available, there is no extra velocity available to close-the-gap created by the sudden spike in pull. The more push falls behind the faster pull increases.



Daily Foods and Goods after the 2011 Tohoku Earthquake (March 2013)

Yet even with the surging demand of real-need and feared-need, supply capacity during the Triple Disaster mostly met or exceeded demand. The source network persisted. One post-event analysis found that only yogurt and fermented soybeans (natto), among 214 products examined, experienced sustained shortages. Still, the distribution challenge was enormous. Capacity proved sufficient. Deploying actual capability was very complicated. Dealing with hoarding was tough. Responding to the active suppression of the supply network was even more difficult.

In the immediate aftermath of the earthquake a public safety perimeter was established for a wide expanse of northeast Honshu. Normal supply chain operations would have been very difficult in any case but for the first several days the military/police perimeter suppressed whatever capacity might have been deployed. The result was starkly insufficient supplies moving to survivors. On March 16, 2011, here is what I wrote to those with whom I was working to unleash the preexisting push network:

> Most major transportation arteries survived the quake. The tsunami took out some big pieces, but that was in a very contained area. Despite this, the amount of re-supply moving into the impact zone to support those sheltering-in-place and evacuees has been very slow. I have not been able to find/hear anything I consider authoritative, but given the strategic capacity available, the lack of forward deployment has been a puzzle. It's still too soon to draw any conclusions but three "suspects" are emerging:
>
> 1. Yesterday the Japanese Department of Social Services actually ordered a "pause" in resupply to the Northeast because the DSS was not sure the supply was going to the right places and it did not have "precise information" or a

"holistic picture." I might curse but have forgotten the Nihongo curse words I once knew. [I worked in Japan for a few years in the 1980s.]

2. For two days I have been hearing rumors that trucks have been held back from going in because they don't have reasonable assurance of being refueled to get out. This morning (Thursday in Japan) the President of the largest Japanese business association is quoted as saying, "Though companies are trying to send relief supplies, they cannot secure fuel for returning," Yonekura said, stressing that gasoline stations along expressways and supply roads are in need of swift supplies of gasoline." This is the first sort-of-confirmation I have seen in writing.

3. Credentialing and perimeter controls are, of course, causing problems. From this distance (and my on-the-ground sources don't have the eyes-and-nose for such things) I don't know if the credentialing is especially egregious or just standard. I will admit to deeply heretical thoughts regarding the utility of credentialing in any true catastrophe.

It took almost two weeks, until March 24, for efforts at perimeter control and replacement supply chains to be mostly abandoned (other than proximate to the Fukushima nuclear power station). Removing these constraints allowed the robust preexisting push network to finally engage the disrupted pull network. Fundamental to this progress was the ability of supply chains to flex sources and routes to fulfill pull. According to one 2014 assessment of humanitarian logistics, widespread hunger was only avoided when:

> ... trucking/distribution companies (e.g., Yamato, Sagawa, Nittsu, and Akabo)—because of their role in the food and retail sectors—were in a position to know that the private sector supply chains had been severely disrupted, and that the public sector was not ready to fill the gap. They recognized that a huge humanitarian crisis was underway and that without their intervention things would get much worse. Independently of each other, they approached local officials during the period March 15th-19th and took the unprecedented step of volunteering to do local deliveries of relief aid... The companies paid for the costs of the local distribution and the supplies that they distributed during the first week; and the costs (except fuel) of the hundreds of trucks and drivers that they volunteered for almost a month...

Following are real-time observations regarding how networks adapted. These observations were blogged by officers of the Foreign Agriculture Service at the United Sates embassy in Tokyo:

- **As of March 15**: "Major supermarkets such as AEON and Ito-Yokado cannot deliver to their stores in the emergency area at this time. They are sending noodles, water [to the government] for relief supplies and trying to keep up with stocks of water, cup noodles and batteries at their stores in the affected area, but are having difficulty. Kokubu, a major food wholesaler, says that it's hard to tell at this moment when infrastructure will recover. At present, the guesstimate is at least one week from today (March 15) to restart distribution of foods. The wholesaler's 25 storage facilities in the effective region, Tohoku Region, are not operative due to power black-outs… hospitals are not receiving enough food to feed their patient populations."

- **As of March 16**: "Seven-Eleven Japan, the biggest convenience store (13,000 outlets), improves its supply ability better day by day. 7-11 Japan is able to shift its distribution system and is able to adapt the Kanto logistic network to serve the Tohoku region, and then use other plants west of Tokyo to serve Tokyo. As of March 14, both Lawson and 7-11 Japan resumed business in more than a half of shop operations in Tohoku region. Lawson resumed operation of 450 outlets out of a total of 810 in Tohoku region. 7-11 also resumed sales at a 450 outlets out of a total of 920 in the region… Major food wholesalers, Kokubu, Ryoshoku and Nippon Access, have received double the orders from retailers. Wholesalers are maintaining ordinary operations at their warehouses in the Tokyo region. According to the Asahi Shinbum on March 15, sales results of the major retailers jumped dramatically in last two days. Purchases of bottled water vaulted to 10 times, Natto 3 times bigger, Tofu 1.7 times more, milk 1.5 bigger. Sales of chicken rose 9 times more than the sales of same period of last year, canned food 3 times bigger, rice 1.6 times more... Rice, toilet paper and other daily necessities are growing scarce at stores, not only in the quake hit Tohoku region, but also in the Tokyo metropolitan area. But manufacturers across a wide array of industries say they have sufficient capacity to meet the demand. The temporary shortage at retailers is likely caused by such factors as turmoil in logistics networks and anxious consumers stocking up on various goods. Retailers and manufacturers are working to fill store shelves depleted in quake-hit regions and the Tokyo area by using distribution networks and production bases in unscathed in Western parts of the nation."

- **As of March 17**: "Out of 170 outlets of York Benimaru, one of the largest retail grocery chains in Tohoku area, 77 outlets are closed."

- **As of March 18**: "Consumer hoarding behavior, rolling blackouts, and the lack of fuel continue to wreak havoc on Japan's food supply system. In response to nation-wide retail level food shortages the Japanese government has made strong overtures to the Japanese people to be judicious in their food purchases... Local retail stores in Tokyo, away from the affected areas, are constantly busy restocking shelves while worried consumers continue to purchase items just in case another disaster occurs. The items that stores can't keep pace of are bottled water, rice, eggs, bread and bread products. Milk purchases are limited to one carton per customer. As already reported, deliveries are slow because truckers can't get sufficient fuel due to high levels of consumer gas purchases and the compromised fuel transportation infrastructure. With regard to gas supplies, prices are going up quickly throughout the nation. Regular gasoline has gone up from about 140 yen ($1.75) per liter to 158 yen ($1.97) per liter, and most stations are limiting customers to 20 liters or 3000 yen per visit."

- **As of March 22**: "Some semblance of normalcy is returning in the Tokyo area. Supermarkets that were having difficulties restocking their shelves are now finding it easier, but shelves are still lacking the usual colorful packages, lined neatly in a row. This differs by region and town, and even sometimes by store. Rice was almost gone from one store in the Akasaka area, while another store, about a block away had ample stocks. There seems to be a lull at different locations and at different times. This will most likely continue because trucks still cannot get sufficient gas to make deliveries."

- **As of March 24:** "NTV reported at 10:13 that there continues to be a serious shortage of food in Ishinomaki, Miyagi, where nearly 80,000 people are dependent on food distribution. The network said that only 110,000 loaves of bread and 60,000 "onigiri" rice balls were delivered to shelters there on Thursday... one shelter in the city could only serve one loaf of bread and one onigiri per person for Thursday night and Friday morning." On March 24 the Tohoku region perimeter was lifted. Despite fuel shortages, this allowed private trucking to operate across most of the Tohoku region.

- **As of March 28**: "On Friday we reported that AEON stores have reopened stores in the affected area. Today, Reuters reported that Wal-Mart will re-open 12 of its Seiyu stores in Japan which were affected by the earthquake, and is hoping to open the remaining 12 impacted stores as soon as possible. Wal-Mart has 371 stores and 43 deli outlets in Japan, of which 24 were affected by the March 11 earthquake and tsunami." Supply capacity and capability were restored to most areas once restrictions on trucking were lifted.

- **As of March 31**: "A growing number of Japanese food makers and retailers are turning to emergency imports to cope with shortages caused by the recent disaster. Aeon Co. has announced plans to import large amounts of food and sundries, purchasing 1,500 tons of onions and 500 tons of carrots from Australia, among other items. Several firms announced to import bottled water from South Korea, Canada, and other countries... Dairy products are still in short supply in eastern Japan as scarce packaging materials such as paper cartons hinder production. Yogurt output, for example, cannot keep up with demand due to rolling blackouts, and supplying products from western Japan is not practical because milk is highly perishable.

In March 2011 the grocery supply chain in Japan demonstrated considerable resilience. It did not collapse under the pressure of extraordinary and extended hoarding in one of the densest urban areas on the planet. Once roads were passable and the perimeter was lifted the freight network responded creatively and even courageously to the needs of survivors across Tohoku.

The Giant Component feeding Kanto (Greater Tokyo, population over 42 million) had the capacity to gap-fill the lost feeding and hydration capacity serving Tohoku (population less than 10 million). Except for dairy and natto outputs, food processing concentrations were not seriously impacted. Fewer trucks and truckers were available. But with extra hours and reduced deliveries elsewhere the highly percolated Kanto network shifted volumes and velocity toward Tohoku. The earthquake and tsunami seriously punctuated pull across the impact zone. But push was disrupted much more by perimeter controls around the impact zone and hoarding outside the impact zone.

Kanto and Tohoku comparative population density

Japan was better prepared for the Triple Disaster than any other society on the planet. Thousands survived because of long-term mitigation and preparedness. Roads were rapidly repaired. Information was widely shared. Neighbors supported neighbors.

Potential destruction and disruption had, however, been seriously underestimated. In pre-event planning and preparedness, the population's dependence on high volume, high velocity supply chains had gone largely unrecognized. Rather than focusing on Supply Chain Resilience, Japan's disaster response strategy tried for supply chain *replacement* with relief supplies delivered through a public sector process. In a 2014 assessment the World Bank found, "local government officials without sufficient knowledge, training, or experience in logistics management performed the specialized functions of receiving, sorting, and dispatching emergency supplies at distribution depots. This resulted in confusion and massive congestion of the delivery networks."

A well-intended predisposition for more centralized control resulted in reduced flows. This tendency actively suppressed the adaptive potential of demand and supply networks for at least two weeks. Survivors received less than half the volumes needed. The World Bank (sometimes accused of its own predisposition for centralized control) derived the following lesson from Japan's experience with the Triple Disaster:

> … the early restoration of commercial demand and supply chains, the rapid restoration of market dynamics, and the speedy distribution of donations to increase local purchasing power and liquidity should be a priority for municipal and local authorities. Job creation and conditional or unconditional cash transfers are highly effective short-term post disaster measures and are often more important than continuing the supply and distribution of relief goods by public agencies. The speed and manner of the transition from public to private supply logistics should be determined by how dependent the affected population is on relief supplies, and on the robustness and speed with which the private sector networks can restore commercial operations.

As outlined in the FAS real-time reports, within four days of the Tohoku perimeter being removed commercial operations surged.

I perceived that following a significant punctuation, complex adaptive systems need space and freedom to rapidly, interactively, creatively – even extemporaneously – reorganize around surviving preferences. In the case of supply chains this will usually be demand signals, either preexisting or newly propagated. Facilitating demand signals is the best way to feed survivors. Where Giant Components survive, where concentrated capacity persists, then preexisting percolation will expedite recovery… if pull signals are sent and we stay out of the way.

But Tohoku is not Tokyo. In March 2011 the comparatively modest needs of less-urban Tohoku could be significantly supported by Tokyo's nearby and enormous Giant Component. Outcomes would have been very different if a 9.0 magnitude earthquake had erupted along the Sagami Trough and a similar tsunami had rushed into Tokyo Bay and its densely populated, infrastructure-rich urban shore.

When and where a Giant Component is punctured its well-percolated network will amplify disruption and destruction. Where concentrated capacity is destroyed, potential Supply Chain Resilience is substantively complicated. Unless another even larger Giant Component is conveniently nearby or the damaged Giant Component can quickly recover, the human consequences will soon be very ugly. The Triple Disaster in Japan taught me that the best preparedness involves the tough task of conceiving how a punctured Giant Component can be rapidly restored as completely as possible. This is achieved mostly through the real-time creativity of private-private and private-public collaboration.

If the Pareto proportion players already know each other and have substantive confidence in a shared strategic concept to reconnect the Giant Component, then there is an outside chance of success. Without confidence in the shared strategy: cut chances by 20 percent. Without a shared strategy: cut chances by 40 percent. If the major players don't even know each other before boom, then there is about an 80 percent chance of deadly failure.

Micro-Case 2: Misunderstandings Multiplied (Superstorm Sandy 2012)

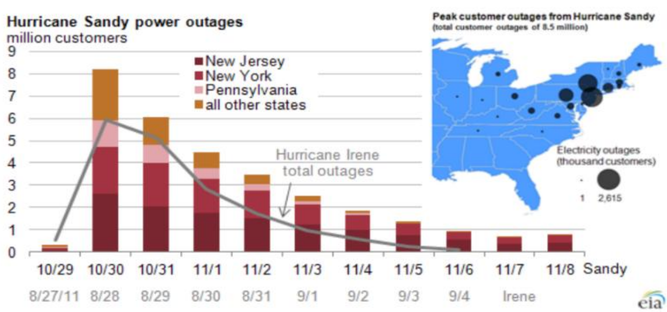
The Japanese had long anticipated and seriously prepared for the sort of seismic event and tsunami experienced in March 2011. The experience exceeded all planning assumptions, but decades of catastrophe preparedness and mitigation still reduced vulnerabilities and, therefore, consequences. It could have been even worse.

In late October 2012 as Superstorm Sandy plowed up the Atlantic coast, too many in the New York metropolitan area discounted official emergency declarations. They depended on cooler ocean temperatures, a wide horizon of targets, and the limits of their own experience to deliver low risk probabilities. In the hours just before landfall Sandy did, fortunately, weaken considerably. But the still huge and powerful storm caused damage, destruction, and more than 230 deaths across the Northeast.

Just in the City of New York, forty-three were killed. Over two million New Yorkers lost power. Nearly 70,000 housing units and 800 buildings were destroyed or structurally damaged. Many bridges, tunnels, and transit stations sustained significant damage, complicating travel and movement of food and other crucial supplies. Sandy resulted in more than $19 billion in property loss across the five boroughs.

I happened to be in New England as Sandy approached. I continued with prior commitments and then stayed put. To get home I would have to travel through the impact zone (or way around it), so I needed to assess options. I was also curious to watch response and recovery. By Halloween a Connecticut venue gave me good access to New York broadcast media (landfall was late afternoon on Monday, October 29 near Atlantic City, about 125 miles south of New York City). I am not a frequent "first responder". I could, however, look, listen and pass along what I perceived.

Given the hard-hit on a not entirely prepared Giant Component, myriad problems percolated through the dense nodes and links of the New York metro area. Wind and water played havoc with the electrical grid. Many elderly residents in tall buildings – now with no working elevators or refrigerators or microwaves – were hungry and trapped. If the chronically ill needed their pharmaceuticals chilled or re-filled, this was now much more difficult. Most groceries, pharmacies, and fuel stations did not have back-up power or, as a result, telecommunications, and credit-card processing.



Grid loss and flooding of communications nodes meant about a quarter of regional Internet connections, cell-sites, and landlines were mute. Some local networks were entirely gone. On November 1 the Federal Communications Commission reported:

> … restoration efforts in the hardest hit areas – including New York and New Jersey – continues to be more difficult. Replenishing fuel supplies for generators that are enabling communications networks to continue operating is a particularly critical challenge… Based on data from 10 a.m. this morning, the number of cell site outages overall has declined from approximately 25 percent to 19 percent. This figure includes many cases where cell sites that are otherwise operational are effectively inoperable because of outages in other parts of the communications infrastructure, which is highly interdependent.

With the grid gone back-up power depended heavily on gasoline or diesel fueled generators. But without the grid, pumping fuel was often not possible. Given the damage done, disentangling and reconnecting the grid would take time. In the absence of electricity, a "shortage" of fuel became the cause-célèbres. In a February 2013 After-Action, the US Department of Energy explained:

> Wind and flooding caused damage to critical fuel facilities such as terminals, pipelines, storage facilities and truck racks, as well as to the electric power infrastructure that

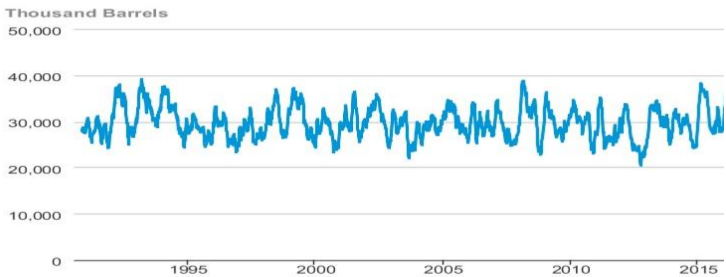
> energizes those facilities. This led to significant shortages of fuels in the affected regions. Docks, control systems, vapor recovery units, and electric switching gear within facilities sustained serious damage. Replacement of parts and components and the complexity of the systems required time and technical expertise to safely restore services. Simultaneously, retail gasoline stations were without commercial power and/or fuel supplies in many instances, and those with power quickly ran out of fuel. The combined effects of damage to terminals, loss of electric power, and high demand for fuel led to shortages and long lines for fuel across the region. Gasoline rationing policies were eventually implemented, first in New Jersey and later in New York.

This is a mostly accurate summary of a very complicated cause-and-effect context. In my judgment the next to the last sentence is missing one word. It should read, "The combined effects of damage to terminals, loss of electric power, and high demand for fuel led to <u>retail</u> shortages and long lines for fuel across the region."

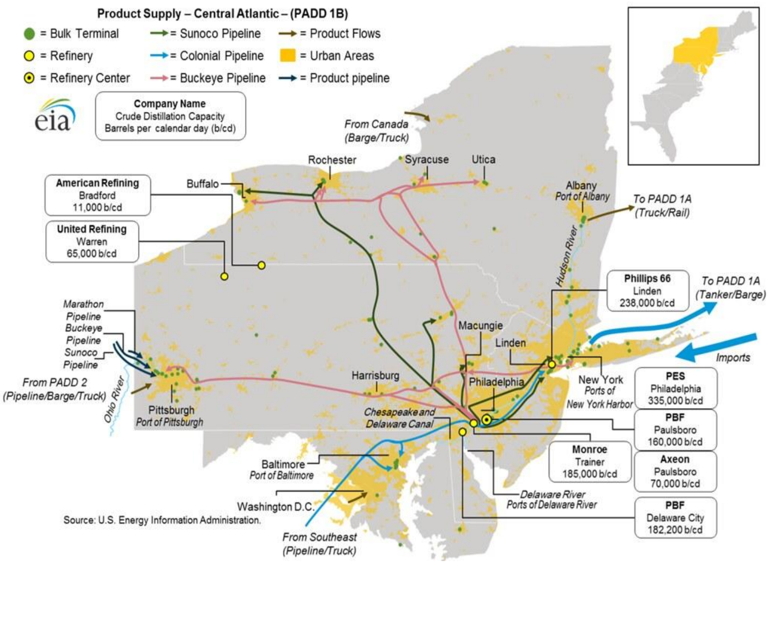
The second sentence in this DOE summary can be misleading: "This led to significant shortages of fuels in the affected regions." In the immediate aftermath of Superstorm Sandy there was not a shortage of vehicle fuels in Sandy-impacted regions. The widespread *perception* of a fuel shortage became a strategically insidious and expensive distraction. According to the US Energy Information

Administration, at the end of the week *before* Sandy hit there were 23,245,000 barrels of gasoline available in the Central Atlantic (PADD 1b) region. At the end of the week after Sandy's Monday landfall there were 22,935,000 barrels in regional inventories. Two weeks after landfall there were 22,249,000 barrels. This was the lowest it got, see the chart on the next page. Rather than a fuel shortage there were a series of punctuations that reduced fuel flows between robust regional fuel storage facilities and higher than usual fuel demand. There was a serious fuel distribution problem, not a supply problem. A distribution problem requires different fixes than a supply shortage. Trying to fix a distribution problem with additional supplies will not fix the problem and can even make the distribution problem worse.

Weekly Central Atlantic Ending Stocks of Total Gasoline



Before and after Sandy, the New York metro area received most of its fuel supply via pipeline, ocean going barge, and tanker truck deliveries from regional refineries. More than a decade later the largest regional refinery has since closed but these three flows continue to constitute most upstream volumes. A significant proportion of these flows are discharged into tank farms that are concentrated along the New Jersey shore "behind" Staten Island (see photo on page XX). Precisely sizing fuel flows is an inexact, constantly shifting process. But in 2012 roughly one-fifth of refined fuel consumed in the Central Atlantic (see map below) was refined in the Central Atlantic. A bit less than one-fifth arrived by ocean barge. The remainder mostly arrived by pipeline, especially from the Colonial Pipeline flowing between the Gulf Coast and Linden, New Jersey.



Sitting in a Connecticut hotel room with grid power, working landline, cellular connections, fast Internet, and multi-channel cable television I spent most of Halloween and All Souls Day watching, listening, exchanging notes with operators, nagging some friends in the utility sector, and working to diagnose what was happening, not happening, and why. Late on November 1 and before dawn on Friday, November 2 I sent personalized emails to several federal officials and corporate executives (with many embedded links, still underlined below and available in the research bibliography on page XXX). Below is a generic excerpt. The bold bits were in the original.

> **Roughly 25-30 percent of regional fuel refining is offline**. The Colonial Pipeline is expected to resume deliveries to the New York metro market on November 2. This major source of Gulf Coast petroleum product has been shut down since October 29. Late November 1 the Ports of New York/New Jersey reopened to maritime fuel deliveries. **Availability of supply is not the fundamental problem.** Roughly 75 percent of the New York metro's gasoline supply is distributed from terminals in the Linden, New Jersey area. One company executive estimated the terminals at his site could take four to six weeks to repair. **Many gasoline terminals do not have electricity to pump product.** Utilities anticipate this issue may be resolved over the weekend. Because of power outages many gasoline service stations cannot pump what they have in their storage tanks. Mike O'Leary, vice president of

Raceway Petroleum Inc., based in Piscataway N.J., said only three of its 50 stations "were able to open with power restored" to run gas pumps. In Paterson, N.J., the state's third-largest city, the Police Department was trying to negotiate emergency contracts for gas, and short of that, said it would beginning siphoning it from other city vehicles to keep police cruisers running. The EPA has issued emergency waivers through November 20 related to Reformulated Gasoline Requirements to maximize gasoline availability in states impacted by Sandy. *Regarding the ports*: I understand [name of US Senator] office really pushed to get ports re-opened to deal with gasoline "shortages"... I am being told **the biggest problem is not the supply of gasoline but the ability to transfer existing stocks into tanker-trucks**. This situation is exacerbated by the co-location of most gasoline terminals in Linden. Also related: anti-gouging legislation -- and [Governor's name] forceful promise to prosecute -- has removed any incentive for full tanker-trucks to be diverted from more distant locations (especially south) into New Jersey.

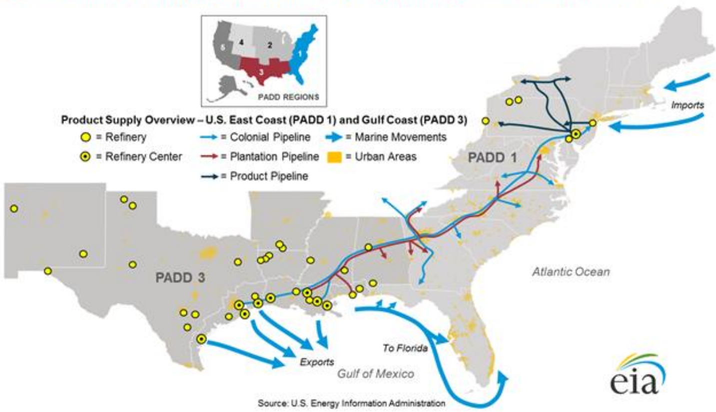
The Senator's and Governor's names have been removed. Their behavior was not a stupid mistake or personal failure. These and plenty more smart, well-intended, highly motivated decision-makers just did not know how the fuel supply chains serving their region operated and how this preexisting capacity and typical behavior could constrain or deconstrain – even *empower* – their strategic outcomes.

You may already be better than most of these decisionmakers at discerning demand and supply dynamics. You may perceive that a Giant Component has been hit and understand what that means. You may already be more competent to diagnose differences between a supply problem and a distribution problem. One reason for writing this book is to help many more see, hear, and share a strategic sense of flows and flow punctuations. More than a decade later – after plenty more real-world examples – the ability to do differentiated diagnosis remains reasonably rare. I am embarrassed and sorry to report that my post-landfall personal emails were mostly ignored. But one trucking executive with a couple of extra generators asked me to go to Linden to see if, how, and where these assets could help.

In 1907 John D. Rockefeller and his Standard Oil company acquired property south of Linden along the Arthur Kill waterway. By 1908 the Bayway refinery was converting raw petroleum (mostly from Pennsylvania) into refined products for the New York metropolitan market. The refinery expanded rapidly as increasing use of internal combustion engines required gasoline. Other refineries were constructed nearby. Various refinery services and infrastructure, including pipelines, followed.

This capacity cluster eventually also received raw petroleum by ocean barge and tanker-ship, mostly sailing from the US Gulf Coast. Early in World War II the "Big Inch" and "Little Big Inch" pipelines were built to transport raw petroleum from the Gulf Coast to Midwest and East Coast refiners while avoiding Nazi submarines. Linden was the terminus for the "Little Big Inch" pipeline. In the early 1960s the Colonial Pipeline was constructed from near Houston, Texas to Linden to supply products refined on the Gulf Coast to be consumed all along the route—by 2012 this included about 700,000 barrels per day for the New York metro market.

Figure 3. U.S. East Coast (PADD 1) and Gulf Coast (PADD 3) transportation fuels product flows



Over the last century, Linden (and nearby) has emerged as a "London Bridge" for fossil fuels, facilitating both push and pull across a wide region. One energy analyst has written of New York Harbor, "...products from the Gulf Coast (having arrived by pipeline) and abroad (having arrived by tanker) are traded along with supplies from area refineries; the aggregate New York Harbor supplies are redistributed by many players to points west and northwest (pipeline) and northeast (barge)." As we have seen elsewhere concentration started and accelerated. More and more nodes became tightly linked. For most of the last half-century a map more or less like that on the prior page has been strategically accurate. On good days I can view this as a diversified cluster network. On bad days it seems to behave more like one tightly concentrated, treacherously interdependent, especially huge Giant Component.

Friday night I topped off my car's gas tank with as much fuel as it would take. Only six percent of electricity customers in Connecticut were without power, but almost a third of New Jersey customers remained off the grid. At dawn on Saturday, November 3, I left for Linden.

Of seventeen New Jersey fuel racks (sometimes also called fuel terminals) ten were non-operational on Friday night. I chose three near Linden as destinations.

Most fuel racks in the United States are associated with a pipeline, either a short connection to a near-by refinery or maritime dock or a much longer link to far-away refineries and/or tank-farms. Linden has several tank farms, as seen in the aerial photo on the next page.

Fuel racks are wholesale refueling facilities for tanker trucks that deliver to retail fuel outlets and other bulk customers. Big rigs pulling 11,000-plus gallon wagons drive up, fill up, and head out. The high-speed pumps are powerful, but the rack's technology is not especially sophisticated. Throughput is decided by how many bays are available – four to seven is typical – and how quickly (and safely) drivers handle fill-ups and payments. The bays are often full in the early morning (after sunrise) and then there is usually a second, smaller surge of fill-ups in the afternoon. Below is a photo of a nine-bay near Linden.

I had never been to Linden before. The first fuel rack I found almost seemed abandoned: gate locked, no lights, no activity. At the second rack a security guy told me power had just been restored about an hour before, trucks were already lining up. They did not need any help from me. At my third stop the gate was closed but there was a skeleton crew, two security guys and one operator. He knew the power was off. He knew he should call his boss if the power came back on. He did not know about an emergency generator. He was hesitant to call his boss about my offer for an emergency generator. While we were talking the power came back on.

I later learned that on this Saturday, five days after Sandy's landfall, most of the electrical substations around Linden were repaired or in any case reenergized. This allowed local electricity distribution lines to be reconnected to regional transmission lines, resuscitating significant parts of the grid. As more substations restarted, most of the fuel racks did too. As more fuel racks opened, the tanker truck fleet could be distributed across more bays with less waiting: resulting in much more velocity. With increased velocity, more fuel volume was distributed. More fuel stations could be refilled more quickly. With many retail fuel stations still not on the grid, it was a bit easier to keep those on the grid resupplied. When gas stations with power stopped running out of fuel, this reduced nervous buying. Reduced pull velocity helped push velocity maintain constant flow.

I let the trucking executive know power was back on without our help and drove home on Sunday. Monday I offered the following explanation/diagnosis to some colleagues:

> At landfall the Northern NJ electric utility did not know that four or five medium sized commercial customers (fuel racks) in and around the Port of Newark were fundamental to gasoline distribution in the NY metro region. No one had ever communicated any priority for these players or their place… In fact, because this place encompasses very few residences and no health care facilities or police stations (there are two fire stations) their place was low on the priority list. Once information on the real priority of this

place broke through the cacophony of the crisis – including lots of noise focused on a non-existing problem with insufficient supply – fixes were implemented pretty quickly.

More pre-installed emergency generators at the fuel racks and retail outlets would have been helpful. Most of the New York Harbor fuel racks now have those in place. Every fuel rack I have visited in any Gulf Coast state has emergency generators. But it is wise never to assume that electrical back-up is available or reliable or can be readily refueled.

Driving into Linden I passed many orange-coned, yellow-taped, closed retail fuel outlets. There were long lines at each of the rare operating pumps. Same scene most of the way to Philadelphia. I was also getting twice-daily email status updates for reopened gas stations. Using credit card transaction data, it was possible to assess how well the retail fuel network was healing. By Monday, November 12 – two weeks after landfall – 414 of 788 New York City retail fuel stations had power, fuel, and credit-card transaction capabilities, 810 of 1472 Long Island gas stations were selling, and 1793 out of 2944 New Jersey fuel retailers were making credit card transactions that indicated fuel was being sold.

In real-time this was very confusing. The noise level of contending claims and plausible possibilities discouraged any certainty or much consistency. But I also hope a few core characteristics of high volume, high velocity networks are beginning to emerge from the fog.

Giant Components are often stuck out of the way. In many cases Giant Components are quite purposefully discreet. But they are almost always too big to hide. Once you start looking and know how to look, they show up. The Linden tank farms are seen by thousands of passengers arriving or departing from Newark International Aiport, if they are not mesmerized by the Manhattan skyline. Especially in a free-market economy there are usually credible sources for sizing the flows of Giant Components. In the case of fuel, the US Energy Information Administration regularly releases rigorously gathered data. Reports are available for real-time spot market activity.

The interdependencies of Giant Components are seldom top secret. Grid loss is not rare. Long-term, wide area grid loss is less frequent, but well-known. How do you pump fuel with no grid? How do you pump water? How can cell-sites continue to operate without the grid? How does gasoline get from the refinery into vehicle fuel tanks? How do you maintain freight velocity when and where the grid is gone, communications are spotty, and need is profound? Potential punctuations are prolific. Answers often remain elusive, especially in the ambiguous context of real-world disasters.

There is a body of evidence and a mind-map that I have found helpful in these circumstances. When network scientists perceive non-random densification of links between nodes these are sometimes called *communities*. The convergence of pipelines around any petroleum refinery is an obvious such community. A Giant Component is always a community of communities – a set of relationships – in which participants change-together, share-together, partake-together (derived from the Latin *communis*). The quality of sharing, partaking, and changing can, however, vary dramatically across a Giant Component. Community analysis attempts to tease out these qualitative differences by partitioning the network in terms of qualitatively relevant inputs and outputs.

Some network science approaches to community analysis give particular attention to *modules*. In this context modules are recurring functional interactions that size and direct network flows. The interactions between pipelines, tank farms, fuel racks, tanker trucks, roadways, the grid, and much more are all potential modules. In many cases the most influential modules co-locate to produce a network with hourglass characteristics. Here's how Constantine Dovrolis, a network scientist at Georgia Tech, and his co-authors explain the modularization of hourglass structures:

> …many complex systems, both in technology and nature, exhibit modularity: independent modules, each of them providing a certain function, are combined together to

perform more complex functions. Additionally, modular systems are also organized in a hierarchical way: smaller modules are used within larger modules recursively. Examples of such systems exist in a wide range of environments: in natural systems, it is believed that hierarchical modularity enhances evolvability (the ability of the system to adapt to new environments with minimal changes) and robustness (the ability to maintain the current status in the presence of internal or external variations). In the technological world, hierarchically modular designs are preferred in terms of design and development cost, easier maintenance and agility (e.g. less effort in producing future versions of a software), and better abstraction of the system design.

Big flows almost always depend on a whole host of discreet interactions. A driver needs to get to the tanker truck. The tanker truck needs fuel to go. The tanker truck needs most of its tires to stay inflated. The truck needs roads to be accessible between where it was parked and the fuel rack. Grid or emergency power is needed to pump the fuel to the rack and into the tanker truck. The financial transaction system needs to still work or be quickly replaced. Roads to the retail location need to be open. Et cetera, etc. Each of these independent functions are often modularized to perform more complex functions. The original functions created for the 1907 Bayway refinery have been easier, cheaper, and quicker to supplement than re-create somewhere else. Existing functional modules can be adapted to serve multiple communities. The Colonial Pipeline's discharge is sold to many buyers. Dovrolis et al assume, "that systems in both nature and technology care to minimize the cost of their interconnections or dependencies between modules." That's what I see too. Dovrolis, Siyari, and Dilkina abstract these predispositions in the following image.

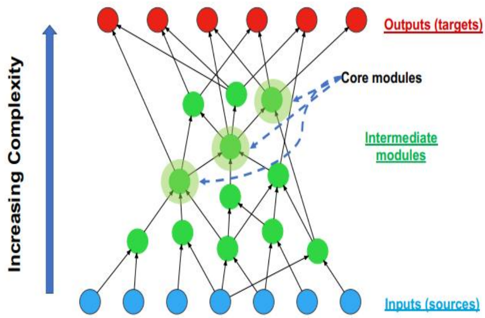
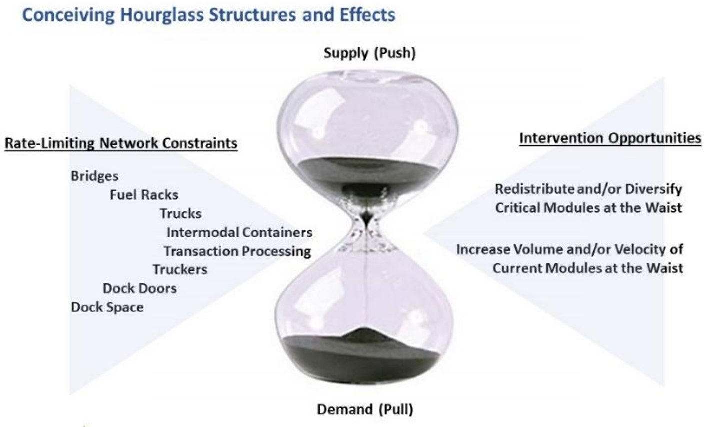


Fig. 1: A hierarchical system is represented as a directed-acyclic graph in which each module is shown as a node, and the dependencies from more elementary modules to more complex modules are shown as upward edges. The hourglass effect occurs when the system of interest produces many outputs from many inputs through a relatively small number of intermediate core modules (here, highlighted nodes with transparent surroundings) [31].

For better or worse – accurately or inaccurately – I translate these nuanced insights of network scientists into my own (too-?) simple hourglass-like abstraction. I have flipped inputs (sources) to the top to imply the contents of the top bulb pushing through a neck of *multiple* modules to deliver what is pulled by the lower bulb. When I see flow slowing or stopped, I try to find the neck of the hourglass to check module throughputs. To facilitate flow, one or more modules often need to be cleared.



Some network scientists use "community" and "module" interchangeably. Perhaps it is the technical characteristics of many high volume, high velocity supply chains that prompt me to prefer a conceptualization of distinct communities that share multiple modules. In any case, I am not alone in perceiving risks embedded in how these key contributors to capacity are shared. In 2019 Sun, Zhang, Feng et al examined many "open questions" around community risk in real-world networks. They wrote:

> Networks in nature not only depend on each other but also have internal community structures, such as infrastructure networks with links within and across geographic regions. The communities play an important role when the networks undergo localized failures in specific regions, for instance when natural disasters or economic sanctions disrupt a local community region and consequently

> influence the whole system. How a disruption in one community propagates through the entire system is a crucial, but still open, question… Our analysis reveals that such a system has rich phase transition behaviors that are much more complicated than interdependent networks without community structures. In particular, we find both theoretically and empirically that network robustness changes abruptly from safe to vulnerable as the strength of the community changes. The safe region of the system is characterized by the lack of phase transition phenomenon, i.e. the system does not disintegrate even with one whole community fully removed from the system. The vulnerable region is when phase transition is present, i.e. removing enough fraction of one community will disintegrate the whole system.

I perceive – and suggest – that in the most densely percolated networks, when most of any module – such as fuel racks – is punctuated, the whole system's flows will suddenly and dramatically diminish. So, when you see a Giant Component, look for the principal communities associated with the Giant Component, and then look for modules – functional sources of interaction – that several communities share. There is where your whole system is probably *proportionally* most vulnerable.

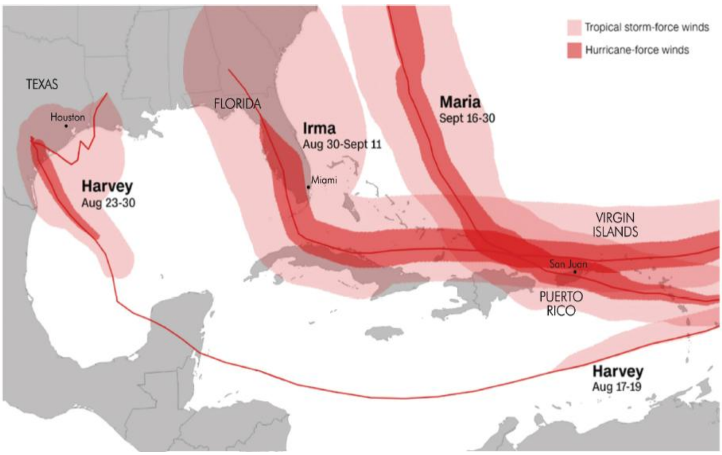
Micro-Case 3: Distance, Density, Mistaken Identities (Puerto Rico 2017-2018)

The 2017 US Hurricane Season included Harvey hitting Houston hard in late August. About two weeks later Hurricane Irma visited most of Florida. Hurricane Maria, the year's most intense tropical cyclone, made landfall in Puerto Rico on September 20. The National Academies of Sciences, Engineering, and Medicine has published a report on all three storms entitled, *Strengthening Post-Hurricane Supply Chain Resilience.* Here is how this study summarizes Maria:

> Less than two weeks after Irma, Maria was declared a hurricane, and warnings were issued across the Caribbean. The storm continued to strengthen, and on September 19, 2017, Hurricane Maria passed over St. Croix in the U.S. Virgin Islands, destroying much of the island's buildings and communications and power infrastructure. On September 20, Maria made landfall in Puerto Rico, still at Category 5 strength. The storm moved slowly across the island, dumping more than 30 inches of rain. By the time it eventually weakened, the entire island's power infrastructure was destroyed, and 100 percent of customers had lost service. Over the course of the next few days, the Puerto Rico Electric Power Authority worked with the Department of Energy, the Department of Defense, and FEMA to distribute fuel and generators in order to keep critical infrastructure online across Puerto Rico and the U.S. Virgin Islands. As ports and airports reopened over the

coming days, more shipments of critical relief supplies were brought in. In late September and early October, the Department of Defense provided a large contingent of employees to support response efforts in the U.S. Virgin Islands, including bringing the Navy ship Comfort to San Juan for additional medical support. However, it was not until many months later that services for potable water, electricity, and cell phone connection were fully restored across the islands.

I worked with FEMA during response to all three storms and later did related field research for the National Academies. Following are several lightly edited pages from one of the Puerto Rico case studies developed for the National Academies assessment.



Hurricane Maria made landfall just south of Yabucoa at dawn on Wednesday, September 20. It was a strong Category 4 storm with winds exceeding 150 miles per hour. With Thursday's dawn Jose Perales, manager of Ralph's Food Warehouse, made it through flood and debris to check the store. His typical 20-minute drive took over forty. In several places the store's roof was gone. He guessed that 30 percent of his inventory had been ruined by rain. But diesel generators had kicked in as intended.

By early Wednesday afternoon the Mi Gente grocery high in the mountains of Naranjito and Comerio, south of San Juan, was reeling from wind and rain. Landslides had already closed Route 167 along the Rio de la Plata into San Juan. The store soon went dark. It would not be reconnected to the grid for another six months. The store stayed locked through that first day and night. Overnight the wireless tower connecting the ATM and credit card machine to the outside world fell hard.

Both Ralph's and Mi Gente – and many more – are supplied from the state-of-the-art warehouse and distribution center[3] for B. Fernandez & Hnos. in Bayamon, just west of the Port of San Juan. On Tuesday they consolidated their trucks, trailers and containers in the freight yard. The same steel phalanx was organized at Puerto Rico Supplies Group immediately to the north, Jose Santiago Food Service Distributors immediately to the south, and at V. Suarez just

[3] In contemporary supply chains there is typically a distinction between a warehouse and a distribution center, but at B. Fernandez, the two functions have arguably been hybridized.

across Route 5. The Goya processing and distribution center was just a few hundred feet south across Route 28. As he supervised preparations Angel Vasquez, President of B. Fernandez, wondered how many people could be fed with the food being held just by his company and those of his neighbors (and competitors).

Less than 500 feet behind the B. Fernandez freight yard is the Puma fuel terminal and racks. Tuesday morning scores of delivery trucks had refueled by moving smoothly through 12 bays. But Wednesday morning was as quiet as Christmas. Trucks and truckers bunkered down at home. More than two-million *barrels* of gasoline and diesel were ready[4], but the racks were closed until Maria completed her visit. Wednesday morning, Maria made an especially violent call on the fuel terminal and racks at Yabucoa, disrupting the source for roughly 20 percent of Puerto Rico's fuel until October 3.[5] Wednesday afternoon, Rodrigo Zavala, Puma's Vice President of the Americas, looked out his home windows at the destruction descending around him. His house was shaking. Rodrigo worried about Puma's glass-encased headquarters overlooking the terminal. Could the hurricane glass resist even this?

Far away in Washington DC the night watch gave way to the day watch at the FEMA National Response Coordination Center (NRCC). The NRCC had stood up as Hurricane

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[4] Before the storm Puerto Rico usually consumed about 155,000 barrels of fuel per day according to EIA.

Harvey popped up in the Western Gulf of Mexico on August 25, 2017. It continued operations as Hurricane Irma hit, Hurricane Jose had threatened, and now as the island of Puerto Rico was swallowed whole into Maria's maw. Jeff Dorko, FEMA's Assistant Administrator for Logistics arrived early to catch the departing chief of the night watch. "What are you seeing?", Jeff asked. His colleague responded, "Mostly the whole place go dark. The grid is going down hard."

Along the north shore of Hispaniola three ocean-going barges four days out of Jacksonville anchor as close to land as they can. This is where they will ride-out the powerful waves extending for hundreds of miles in front of the hurricane. The forecast calls for Maria to turn Northwest; if so the cargo of "FEMA freight" will be safe and ready for unloading at San Juan. On board are tons of water, shelf-stable food, blue tarps, and more. The same complement of supplies had been delivered by fleets of trucks to survivors of hurricanes in Texas and Florida. What a month.

Grid Unreliability and Supply Chain Resilience

Contemporary supply chains are dependent on – and usually interdependent with – the electrical grid, telecommunications systems, road and fuel networks, and other sometimes surprising aspects of push and pull factors. Grocers, for example, depend on power systems for lighting, payment processing, climate control, and refrigeration. The Puerto Rican electrical grid is not reliable. Since 2014 Puerto Rican consumers of electricity have experienced service interruptions at a rate four-to-five times the average for the US mainland. A November 2016 "Experts Report" stated, the Puerto Rican electric utility's "generation and transmission facilities are in a state of crisis."

Grocery stores, food processing, and many other elements of consumer demand and supply require reliable water service, but the water sector itself needs power to operate. Over 95 percent of Puerto Ricans are public water customers. The network consists of over 20,000 miles of pipe and 114 filtration plants. In some areas the water system benefits from large surface reservoirs and gravity feeds. But the mountainous interior of the island also features long pipelines that climb over 2000 feet from water treatment facilities. Water is heavy. Significant power is needed to pump volume up and sometimes over the mountains. Most mainlines include back-up electrical generation. Prior to Hurricane Maria 1,348 emergency generating units (EGUs) were deployed across the system. Another 269 EGUs were deployed during the long-term grid outage. Expenses associated with EGU deployment and operations equaled more than 60 percent of total 2017 water authority expenses.

Shippers, wholesalers, and retailers are reliant on communications systems for logistics management, order fulfillment, inventory management, and processing payments. Puerto Rico has been an early adopter of wireless technologies for personal communication, Electric Data Transfer and business-to-business transactions. Since 2008 the number of wireless subscribers in Puerto Rico has grown from

2.54 million to 3.23 million (out of a current population of 3.4 million). More than 50 percent of Internet traffic in Puerto Rico is generated by mobile devices, compared to a US average that has recently ranged from 32 to 42 percent. This widespread adoption of mobile Internet has facilitated significant business-to-business digital processing. Puma, for example, now facilitates bulk fuel purchases through an entirely digital process.

Most telecommunications infrastructure in Puerto Rico is engineered to persist with temporary loss of the electrical grid. Following Hurricane Irma (two weeks prior to Maria) approximately 63 percent of Puerto Ricans experienced several days without electricity. But the Federal Communications Commission reports that in the area of Puerto Rico hardest hit by Irma, 45 percent of cell towers continued to operate and in less than four days the outage had been reduced to 26.9 percent of cell sites in the impact zone. Since the advent of mobile communications quick recovery has been the common experience. This was not the case in the aftermath of Hurricane Maria.

In contemporary supply chains, demand pulls supply. Since the 1980s pull signals have become mostly telecommunications signals. In the last seven to 10 years the signals have increasingly become bits and bytes flowing across the Internet. In calendar year 2016 Puerto Rico recorded \$37.4 billion in total retail sales. Approximately 20 percent of retail sales are transacted using credit, debit or electronic benefit transfers. In 2016 roughly \$5.6 billion was expended at food stores. Approximately 40 percent of all food purchases are made with the Department of the Family's Electronic Benefit Transfer (EBT) card also known as the PAN card. There are more than 35,000 Point-of-Sale terminals in Puerto Rico. Even most cash transactions eventually depend on telecoms (which depend on electricity). In 2015 there were 1,064 ATMs in Puerto Rico.

Responding to consumer pull, the commercial sector exchanges its own business-to-business digital signals. For example, when a fuel distributor places a digital order with a fuel supplier, it is digitally scheduled to receive fuel, and digitally pays for fuel. This seamless processing keeps the flow of trucks moving smoothly through the racks and pushes supply toward demand.

Over the years as the grid incrementally deteriorated, key elements of demand and supply networks attempted to mitigate dependence on the grid. Many residential and commercial customers invested in back-up power generation, typically in the form of 250-watt gasoline-fueled generators sufficient for a few essential services, especially home refrigeration. Much larger diesel-powered generators are utilized by grocery stores, fuel retailers, and other commercial operations. None of these back-up systems are designed to operate continuously over many weeks. Many of the largest diesel generators require maintenance every 500 hours or so. Continuous operation also requires regular refueling. Without fuel and appropriate maintenance generators fail and require specialized expertise to repair or restart.

Puerto Ricans expect annual hurricanes. They have grown accustomed to occasional loss of the grid. When Category 3 Georges hit in1998 less than 20 percent of Puerto Ricans utilized mobile phones. Today it is over 88 percent and business-to-business communications has followed. As Hurricane Maria toppled power transmission towers crossing south to north through the mountains of Puerto Rico, a wide web of dependencies fell with them.

First Week after Landfall: Fuel, Transport, and Cash Complications

On Saturday, September 23, 2017, Jose Perales stood inside his hot, dim but once-again clean and dry store. The roof was patched, spoiled stock removed, and three generators were humming (well, one was growling). Most employees were back at work. The line of customers waiting in the parking lot extended the length of a football field. Local police stood by, but the crowd was patient. The Assistant Manager unlocked the doors at about 7:30 a.m. Customers purchased water, canned meat, and they especially wanted Coca-Cola. The demand for Coca-Cola surged and stayed high for weeks after the storm. "Something sweet for a sour time," Jose decided. The Coca-Cola supply truck was the first vendor to show up after the storm.

Other suppliers – including B. Fernandez – began delivering to Yabucoa on Monday and Tuesday. "We were prepared to load trucks on Sunday, but most of our customers could not receive until Tuesday and several were not able to receive until

Thursday," Angel Vazquez explained. On Monday Ralph's Food Warehouse headquarters in Las Piedras sent one of their procurement staff to Caguas where they had heard a cell signal was available. She was able to tell B. Fernandez and other wholesalers that the Ralph's in Yabucoa was ready to receive. In Puerto Rico most grocery products are Direct Store Deliveries (DSD) from wholesalers. Most of the wholesalers are in the San Juan metro area almost 50 miles from Yabucoa.

"As a rule, the smaller the store, the quicker the recovery," Angel Vazquez (B. Fernandez) observes. "Our largest customers have the most sophisticated systems and were, as a result, the most disrupted by long-term outage of the grid. Our smallest customers, up in the mountains -- even though they had been hit really hard -- were the first to open. They also immediately adapted their orders. Less beer. Lots of canned meat. We sold more Spanish canned fish than ever before."

As a year-round cost-containment procedure, B. Fernandez purchases fuel for its independent truckers from the nearby Puma fuel rack. It is dispersed at the warehouse from its own 10,000-gallon tank and sold to the delivery fleet at cost. As a result, the wholesaler's trucking partners did not experience any fuel shortages during the post-storm period. Many others did experience significant fuel shortages.

The island-wide failure of the electrical grid resulted in simultaneous population-wide initiation of back-up generators. Luis Sanchez, President of the Puerto Rican Licensed Electricians Association, estimates there were more than 100,000 residential electrical "plants" in place pre-Maria.

Most of these are smaller under-5000-watt generators with fuel tanks of less than 10 gallons designed to operate for 10 to 12 hours with enough power to operate a refrigerator, house lights, small appliances, and recharge cell phones. Even many larger commercial EGUs had fuel reservoirs only sufficient for three-quarters of one day.

"Most generator back-ups were installed to mitigate short-term spot outages. Very few were consciously trying for long-term grid replacement." Rodrigo Zavala, President of Puma Americas, (and a resident of Puerto Rico) explained. "There was plenty of fuel, but there was not sufficient fuel storage at the point-of-consumption. Almost everyone needed daily refueling. Suddenly refueling one million additional households once or even twice a day is not feasible."

In recent years Puerto Rico has consumed roughly 2.5 million gallons of gasoline per day. In the immediate aftermath of Maria demand jumped more than 40 percent. Even as late as December when more than 60 percent of grid customers had been restored, average daily gasoline consumption was more than 25 percent above normal.

The increase in fuel demand was essentially simultaneous across the entire island. By Monday, September 25, 2017, a few more than 100 (of 1,100) gas stations were open. Nearly 10 percent of available National Guard troops were assigned to several San Juan metro area stations to encourage calm and public order. Ninety-one fuel tankers were counted making deliveries on Monday, usually with security escorts. Two of five major fuel racks were closed. The other three were operating at less than prior capacity, mostly due to the loss of digital processing capabilities and a reduced number of tanker trucks arriving to be loaded.

Attempting to extend available retail supplies and treat customers fairly, many gas station operators rationed purchases to $10 or $15 per person. While this may well have defused social tension in the long lines, it also made the lines longer as many consumers would empty their jerry cans and quickly return to the line increasing and accelerating expression of demand.

On September 29, 2017, the Secretary of Consumer Affairs (DACO) made retail rationing illegal. "Now there is even more need for gasoline for power plants. The most common hold very little gasoline, to operate eight or 10 hours, and people have to replenish almost daily," Secretary Pierluisi explained. Removing arbitrary limits on consumer purchases reduced overall consumer cycling. Curfew was also extended two hours giving the system more time to meet demand, and by the end of the first week almost 700 gasoline stations had opened. On September 28 the Governor exempted fuel distributors from the curfew, allowing nighttime deliveries. By the beginning of the second week after landfall, the lines at gas stations were much less dramatic. The increasing range of consumer-options and operating hours allowed the fuel distribution system to achieve much more balanced, sustainable and assured through-put. By October 3, 2017, the Puerto Rican fuel distribution system had reclaimed preexisting capacity and was distributing roughly 30 percent more than before the storm.

According to the US Census Bureau, there are about 19,000 people in Puerto Rico involved in moving material of all sorts. There are about 13,000 truck drivers. According to the US Bureau of Labor Statistics there are roughly 8000 drivers of heavy trucks and 5000 drivers of light trucks and delivery vans. All were in some ways victims or survivors of Hurricane Maria. Most took two or three days to do immediate repairs and attend to personal priorities. By Monday, September 25, 2017, many truckers were prepared to return to work, but there were serious impediments.

Many roads remained impassable. In urban areas, even where roads were clear, traffic lights no longer functioned. Communications was minimal or non-existent, so what was open, what was closed, and the condition between here and there was very uncertain. Many independent truckers surveyed the long lines at the small number of operating gas stations, worried about running out of gas, and often decided they needed to know more before restarting their regular routes. There was plenty to do at home.

Not much moved – not nearly enough moved – for the first five days after landfall. The regular flow of food, fuel, and much more was seriously disrupted by lack of electricity, lack of communication, debris in the road, bridges out, complications with fuel distribution and the myriad challenges of immediate recovery. But by the end of the first week each of these impediments was gradually overcome. On Thursday, September 28, 2017, B. Fernandez and its trucking partners moved seven times ordinary daily volume. It was the beginning of a surge that continued through mid-December.

While the pre-existing supply chain demonstrated considerable resilience under duress by the close of the first week after the storm, there were also places entirely cut-off. The Mi Gente grocery store stands at a rural crossroads between mountainous Comerio and Naranjito. It is usually less than 20 miles to the wholesalers in Bayamon. With binoculars from nearby high ridges looking northeast you can find the warehouses. But for the first few weeks following Wednesday's rain and wind, those 20 miles seemed to be 200 or many more. Roads into San Juan were blocked by multiple landslides and wash-outs until September 28, 2017.

Friday is usually the big day for food deliveries. Trucks could not get through on September 22, 2017. But customers did. They mostly purchased canned goods and ice. The store limited each family to three cans and two bags of ice. Still by the end of Friday the ice was gone. The store had frozen meat to sell until on Thursday, September 28, 2017 when the generators ran out of diesel. Over $30,000 in meat and other perishables were lost. Rene Lopez was unable to refuel his generator for two days. In late September he did not imagine depending on his generator for six more months.

With fuel, Rene's diesel generator supplied power. The cash register kept track of sales. But for the first month only cash could be used. The ATM and the Point-of-Sale terminal depend on a rooftop tower to exchange EBT and other digital signals. The antenna had blown down in the storm. After a few days it was erected again, but the tower in Barranquitas did not respond. On Friday, September 29, 2017, Rene was able to drive into Bayamon to place orders and bring back cases of essential products in his own truck. He continued personal pick-up and self-delivery for over two weeks.

Most people paid cash. But over 60 percent of the Mi Gente's customers usually pay for groceries with their PAN card[6]. Many of these customers quickly ran out of cash. In some cases, Rene Lopez resurrected the practice of "fiao" or "Don Fiao", the granting of temporary credit. During the first month regular customers without cash made small purchases using store-credit to be repaid when PAN cards could be accepted again, or other resources were available.

At 8:00 a.m. on Saturday September 23, 2017, the US Coast Guard reopened the Port of San Juan. Shortly after 10:00 a.m. one of the barges that had anchored off Hispaniola began to unload. Over the next six days over 700 loads of FEMA Freight including more than 1.3 million shelf-stable meals and huge quantities of bottled water arrived. The El Rey, another vessel, was scheduled to arrive on October 2, 2017, with 100

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[6] The analogous mainland program is SNAP (Supplemental Nutrition Assistance Program) AKA as food stamps.

fuel trucks loaded with 275,000 gallons of diesel and 75,000 gallons of gasoline. As FEMA relief supplies arrived at port they were quickly trucked to 11 staging areas around the island where they supplemented emergency supplies already stored in Puerto Rico.

In Washington Jeff Dorko and his FEMA-Logistics colleagues worked to enable a minimum of 1.5 million meals per day in Puerto Rico. They aimed to feed, water, and provide essential life-saving services to 20 percent of the population. Some were arguing even this was not enough. On September 25, 2017, the Puerto Rico Department of Housing and Governor's office requested six million meals per day for the following three weeks, with gradual reductions over the following nine weeks. This request anticipated 60 percent of the population would not be supported by preexisting supply chains. In any case, FEMA was pushing every calorie and ounce of water it could procure toward the Port of Jacksonville and any other place there was a vessel sailing or an airframe flying into Puerto Rico.

No one in Washington knew about the Ralphs opening in Yabucoa or the Mi Gente store in the mountains. Had anyone at FEMA Headquarters ever heard about B. Fernandez, a 125-year-old fixture of the Puerto Rican food chain? At the Joint Field Office (JFO) opened at the San Juan Convention Center local emergency management personnel recognized B. Fernandez and even knew its warehouse location. But they did not know it was making food deliveries at seven times the normal rate by September 28, 2017. The JFO was more likely to know that Puerto Rico Supplies, next door to B. Fernandez, had lost its warehouse roof. They were more likely to know which stores could not open because they had no diesel. They were focused on hospitals with no fuel for back up generation. Bad news travels fast. Good news tends to be much more discreet, especially in a crisis.

One month after landfall: Network Recovery, Redundancies, and Interventions

"Sistema! Sistema! Sistema!" Ana shouted. Carlos and Rene came running. Every day since they had repaired their antenna the Mi Gente grocery had checked to see if they had signal. On Wednesday morning, October 18, 2017, there was a return pulse from Barranquitas. Ana danced behind her check-out counter. Carlos laughed. Rene's eyes teared up. Finally, customers could use their bank cards and PAN cards again. The ATM would recognize them again. Many were glad to get reacquainted. Well before the end of the day the ATM was out of cash.

There was still no ice. No more fresh or frozen meat. No fresh vegetables. But the bread trucks were delivering again. The B. Fernandez truck brought cases of SPAM and canned chicken and previously unknown canned products from Mexico and Spain. Deliveries were not yet predictable. There were new drivers behind the wheels of the delivery trucks. They told Ana that several of the usual truckers had taken higher paying routes delivering relief supplies between the docks and government staging areas. Some were even working as translators and navigators for electrical repair crews from the mainland.

The Mi Gente store could now exchange electronic data, but Rene was still driving several miles to use his cell phone to place orders. One month after the storm 16 of 18 cell towers in Comerio were non-operational. In Bayamon and San Juan about half of the cell towers were back online. Island-wide about one-third of cell sites had come back. This provided mobile connections for about 61 percent of the population.

Thirty-days-after landfall roughly 20 percent of Puerto Ricans were reconnected to what was being called the grid. But the south-to-north transmission system was still in tatters, several substations were barely operational, and for many parts of San Juan the source of electricity was not any of the long-time public power plants but temporary recently installed mega-generators.

Those reconnected did *not* include Ralph's Food Warehouse in Yabucoa or the Mi Gente in the mountains, or B. Fernandez in Bayamon or even the Puma Terminal next door.

Connected to the grid or not, by mid-October all the major fuel terminals were operating at or well-above prior output: Puma and Total in the San Juan metro area, Buckeye in Yabucoa, Corco and Peerless in Tallaboa. Eighty percent of gas stations had reopened. There were still some lines. Consumers were still sensitive to keeping their gas tanks close-to-full. The private generator set still had to be refilled daily. But in most places, most of the time, supply and demand had found a new equilibrium.

"Fuel demand spiked and remained at far above normal into November. We – meaning the entire fuel sector – always had sufficient fuel on the island. But our distribution capacity was not sufficient for the new demand. Even worse, in the first several days some of our competitors could not dispense fuel. We had an enormous challenge creating a paper-based replacement for our digital queuing and purchasing process. So, system through-put was significantly constrained just when demand was loudest," is how Rodrigo Zavala summarized the first two to three weeks.

The fuel supply chain in place before Maria focused on fulfilling demand for electric generation by the Puerto Rico Electric Power Authority (PREPA) and for surface transportation. These two requirements accounted for roughly 90 percent of all fuel products consumed in Puerto Rico.[7] In the aftermath of the hurricane, demand by PREPA precipitously declined while demand by thousands of residential and commercial back-up generators soared.[8] The equipment, personnel, and schedule required to serve the prior source of demand was not identical to that required by the new source of demand. Prior demand was a predictable

[8] PREPA uses fuel oil, diesel and natural gas for generation. The private generator set is mostly gasoline and diesel based. As a result, some of the assets used to fulfill demand for PREPA could not be immediately converted to new demand.

pull by a single source. New demand was an unprecedented level of need being expressed at hundreds of local gasoline retailers, even as those same retail locations continued to supply the fuel needed for surface transportation. Two previously separate "pulls" were now combined in the same place. The lack of sufficient storage by the private generator set produced rapidly cycling demand that drained retail stocks much more quickly than the surface transportation pull. This required distribution assets to refill the retail locations much more often, perhaps three-times-as-often, than previously. Refilling capacity is limited by the number and volume of fuel delivery trucks, number of drivers, and number of fuel racks (and truck bays) available.

In the first several days after the hurricane at least three of five major racks were not operating. Driving time for fuel trucks was limited because it is unwise to operate a large vehicle full of fuel after sunset where streetlights are dead and roads have been seriously damaged. These space and time constraints were further narrowed by the loss of digital processing at the fuel racks which as a result required much more time to serve each truck.

"But by one-month-in," Zavala says, "there was already excess capacity on the island, both in terms of supply and distribution. On September 21 (the first day after landfall) the system probably needed 100 more fuel distribution trucks to meet the surge requirement. Thirty days later 250 to 300 trucks had been delivered. Impressive response. But over-supply creates its own difficulties and distortions." In early

October the Public Service Commission of Puerto Rico offered a five-hour course that awarded over 2000 provisional certificates to transport fuel. But according to Rodrigo Zavala, two hundred would have been entirely sufficient. That ten times as many earned the temporary certificate suggests the wild gyrations being experienced by several parts of the demand and supply network.

To ensure movement of relief supplies, FEMA contractors were ready to pay premium prices to truckers. This expedited the movement of the relief supply chain even as it complicated, and arguably slightly suppressed, the ability of the grocery and construction supply chains to surge. Even other public-sector supply chains were impacted. Carlos Contreras Aponte, Secretary of the Highway and Transportation Authority complained to Reuters that his agency was facing serious limitations repairing the road network because "our truck drivers, many have been hired by other companies." Reviewing his repair requirements, the President of the Water Authority said, "We'll never have enough trucks."

Having lost some of their trucks and truck-drivers while trying to respond to demand well above normal, many beverage, grocery, and other wholesalers could not keep shelves fully stocked. Seeing empty shelves reinforced the consumer's sense of uncertainty and increased demand. Seeing empty shelves where there should have been water was especially disconcerting.

By October 20, one month after landfall, more than 70 percent of Puerto Ricans had access to public water. But water quality was widely questioned. Even before the hurricane, many Puerto Ricans preferred to drink bottled water. Coca-Cola, PepsiCo, and Cristalia all maintain large capacity bottling plants in Puerto Rico. Before the storm these and other on-island operations had supplied nearly all local demand with Direct-Store-Deliveries.

During the first month after landfall, while many of these water companies doubled production, they found that demand had more than doubled. Some of this demand came courtesy of FEMA contracts. "In retrospect we should have stayed away from local bottled-water producers and focused on bulk water and bringing in supplies from the mainland," one FEMA official commented. "While the on-island contract made some financial and logistical sense, it screwed up local supply and demand. We basically took product out of the commercial channel, moved it into the relief channel, and probably ended up distributing it less widely – and at a much greater overall expense – than if we had sourced elsewhere for emergency needs and let the preexisting channel respond to retail demand. We contributed to empty store shelves and this had predictable effects on consumer behavior."

Faced with scarcity and uncertainty, consumers hoard.[9] Automobile owners fill-up their tanks when they are already three-quarters full. Grocery shoppers purchase six cans of

[9] Sterman and Dogan, OpCit

SPAM because they are not sure of future supplies. Hospitals nervous about running out of diesel call three commercial providers and their local mayor and the governor's office, trying to increase their odds that one supplier will show up in time. "In effect, many hospitals were sending pull-signals into the supply chain that multipled actual need by three or four or more. No distribution system will ever catch-up with that kind of false signaling," Zavala notes. A 2018 study of Puerto Rican consumer behavior found that for 12 weeks after the hurricane, the frequency of grocery shopping soared from an average of slightly more than one store visit per week to 11 shopping trips per week. Part of this is explained by the loss of at-home refrigeration and cooking capability. But it also reflects a fear-of-missing-out in a time of profound uncertainty.

"Given the cost of repairs, the extra expense of diesel, and all the extra hours worked, the store probably lost money in October," the manager of Ralph's Food Warehouse in Yabucoa says quietly more than six months later. "I really don't recall. That was not my priority. I was just trying to keep things running. We've done fine since. There has been huge customer demand from the very beginning. Our customers are happy to come here."

Unlike the Mi Gente in the mountains, the roads connecting Yabucoa to San Juan were quickly reopened. The store is less than one mile from the intersection with the four-lane Route 53 toll-road. Regular deliveries resumed the week after the hurricane. Ice and meat were the most difficult to get. But in early October the Yabucoa store was the first of 12 Ralph's stores to receive big deliveries of both high-demand products. "I hugged my assistant manager when he told me about the meat," Jose Perales said. "Ralph, the owner, did not believe me at first."

"Toward the end of the second week, maybe Thursday, our fuel delivery did not arrive as scheduled," Mr. Perales remembers. "I was worried we would lose all the progress we had made. But the mayor, he gave us some diesel from the truck FEMA had sent to Yabucoa. So, we made it through okay."

The day after the emergency fuel delivery, a team from Osnet in Humacao came to install a new piece of technology that allowed the Yabucoa store to once again process bank cards and the PAN card. "So, in just one day I went from fearing everything was falling apart to being very happy. Using their cards again allowed customers to get what they needed."

Two weeks after landfall, the Ralph's in Yabucoa restored the power of plastic. The Mi Gente was more typical in not being able to conduct Electronic Data Transfers before the fourth week. But in any case, by October 24, 2017, 95 percent of PAN beneficiaries were purchasing food with their EBT benefits. Four thousand new families had also applied to participate in PAN since landfall.

PAN beneficiaries have incomes that fall below the federal poverty threshold. Over 65 percent of PAN beneficiaries have zero monthly income. Another 31 percent have monthly incomes that are less than half the federal poverty threshold. Food costs in Puerto Rico have been estimated at 9-percent higher than the US mainland average. In 2015 the monthly benefit ranged from $112 for a single-person household to a maximum of $776 for a household of eight…

By the second week in October the grocery supply chain in Puerto Rico was well-on-its-way to restoring demand pull. Once Point-of-Sale terminals could be used, that immediately reengaged over 45 percent of the population who use PAN EBT cards. The same work-around systems allowed other consumers to use their credit and bank cards. As was the case with the Mi Gente in the mountains, ATM networks were also coming back, even while the grid remained mostly down.

By the end of October about five percent of PAN beneficiaries remained outside the reach of grocery and related private sector supply chains. That equates to 85,000 to 90,000 people detached from their regular source of food, which is a significant challenge – anyplace – anytime. Further, there was another segment of the population that was in need even if they were next door to a fully operating grocery store. PAN serves the poorest of the poor. Restoring the ability to use PAN was a huge strategic step. But in the aftermath of Maria many self-sustaining Puerto Ricans were suddenly not employed.

The median annual household income in Puerto Rico is $19,606. Just over 40 percent of households make under $15,000, almost all served by PAN. Another 29 percent of households make over $35,000 (more than 16 percent make over $50,000). This leaves roughly 30 percent of households that are not part of the PAN system and who, probably, have limited cash reserves. Fifty-seven percent of Puerto Ricans have no savings. The longer the crisis – and loss of employment – the more likely this 30 percent segment will need assistance. In the first month after Maria there were 4000 new applicants for PAN.

In the first thirty days after Maria's landfall FEMA procured, shipped, and provided an average of 600,000 meals and 742,000 liters of water *per day*; delivered more than 3.6 million gallons of diesel and nearly 129,000 gallons of gasoline; provided 42,000 tarps and installed 439 Blue Roofs while providing financial, personnel and logistical support for power restoration, debris removal, health delivery and other critical response missions. These resources were delivered at the request of the Commonwealth of Puerto Rico. "They ask. We do everything we can to respond. That's our mission," is how Jeff Dorko describes FEMA logistics. In many cases the Puerto Rico "ask" originated with one or more of the 78 mayors. The mayor of Yabucoa was not the only one who got a fuel truck. The mayor of Comerio specifically asked for help with water purification. The US Army Corps of Engineers purification team set up operations just a few curves down the mountain from the Mi Gente grocery.

At the JFO in San Juan any indication of private sector recovery was welcome news. But mostly they heard about impediments. There was very little strategic sense that one month after landfall, the Puerto Rican grocery supply chain was about 90 percent recovered and by volume-being-sold was operating at well-above pre-storm through-puts. The government-to-government pull and push of the relief channel does not necessarily reflect the pull and push of preexisting – or recovering – demand and supply chains. Often the two networks are separate and parallel. Occasionally they collide.

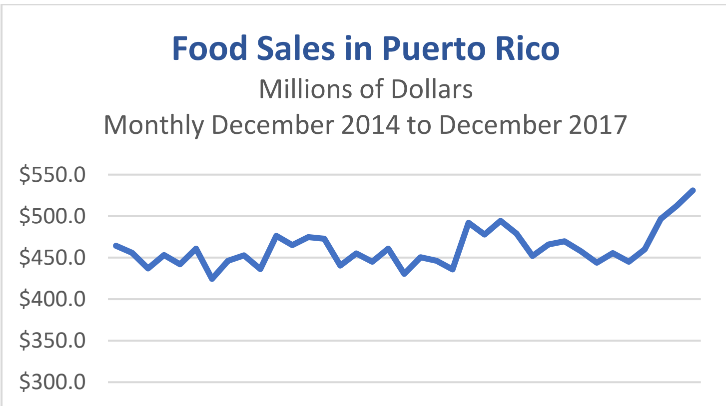
Three months after landfall: A functional system engaging deep uncertainty

Puerto Rico has experienced negative or flat economic growth since 2005. Puerto Rico's population had declined by roughly 10 percent in the 14 years *before Hurricane Maria*. Relocation to the mainland and elsewhere has continued. Given this context, for the last decade many broad measures of economic activity have tended to produce a sense of déjà vu. For example, total retail food sales for July 2008 were $454.8 million. In July 2017 retail food sales were $455.5 million. There are seasonal and monthly variations. As in the remainder of the United States, retail sales are usually highest in November and December. For Calendar Year 2016 the strongest grocery retail results were in December with $494.2 million. Before 2017's stormy September – do not forget Irma – comparative food sales were slightly stronger than in 2016.

For example:

July 2016	**July 2017**
$450.5 mil.	$455.5 mil.
August 2016	**August 2017**
$446.2 mil.	$444.9 mil.

Then in the aftermath of two hurricanes, grocery sales surged: September: $460.2 million, October: $496.8 million, November: $512.6 million; December: $531.0 million. December 2017 food sales were the strongest month since December 2009. This commercial pull and push was happening despite most of the grid still being out and the rest unreliable; even with challenges sourcing product, various distribution bottlenecks, much higher unemployment, the impact of fuel purchases on consumer disposable income, and the giving away of tons of free food.



Source: Government Development Bank: Puerto Rico Economic Indicators

Similar results were experienced by the retail fuel sector: August: $857 million, September: $856.5 million, October: $912.7 million, November: $838.2 million, December: $967.8 million. December retail sales for the fuel sector were the best in three years, even with historically low pump prices. Consumer confidence in the Puerto Rican fuel sector was so strong that in early November the Commonwealth stopped providing regular updates on fuel supplies. No one was worried anymore.

Despite its own very strong sales, many in the grocery industry perceive even better was possible.

"The supply chain was very uneven, rough, unpredictable all through November. We could not get many of the products we wanted or the volume we needed," Jose Perales reports. "Too often our customers were buying what we had to sell, not what they wanted to buy."

"I could not get vessel space for goods I regularly bring from the mainland," Angel Vazquez explained. "FEMA food and more had higher priority. So, we (B. Fernandez) increased buying from Mexico and Europe where I could surge flow with much more confidence. Because we regularly buy and sell many international products, it was easier for us than others to diversify our inventory mix."

"We also lost up to 10 percent of our trucking capacity," the President of B. Fernandez reports. "Several independent truckers went to work moving relief supplies. To fill the gap and increase volume, we helped a small trucking company purchase eight pre-owned trucks. In exchange he hired drivers and guaranteed long-term service to B. Fernandez and our customers."

"Consumer uncertainty was so high that I perceive almost everyone was ready to buy almost anything until sometime in mid-December. There were just too many signals of ongoing disruption. But once the water aisles in the grocery stores were regularly restocked, the market finally began to calm down. Lots and lots of water in the aisles was the signal shoppers finally found to be reassuring, "Vazquez suggests.

Many wholesalers report the available flow of products from the mainland has remained well-below pre-hurricane levels even into the new hurricane season. "It is still difficult for us to get products. Before Maria, we had inventory for 14 to 20 days, but now only seven or eight," Ricky Castro, owner of Castro Cash & Carry to the El Nuevo Dia newspaper. The newspaper reporter adds, "Demand has skyrocketed and is higher than the capacity of the ships… the struggle to find vessel space is shared with dozens in the construction and other industries."

Problems persist. Preparedness for the new hurricane season is weakened. But it is also worth recognizing that even with all the disruption, the grocery supply chain delivered many more calories in the fourth quarter of 2017 (and since) than it has at any time in the last decade (even when there were many more customers).

Ana had shouted, "Sistema! Sistema! Sistema!" The cashier at the small grocery store on a mountain in central Puerto Rico shouted, *The System! The System! The System! We are once again connected to the System*. Then she danced.

Ana does not know the technical details. But she does understand consumer behavior signaled through that data link pulls supplies to the mountaintop. Until that critical connection was fixed, Mi Gente was excluded from the system of demand and supply. Outside that system, expressing demand and receiving supplies is difficult. Once that connection was healed, Mi Gente and its customers were also on the mend.

By statute and policy FEMA's relief channel responds to pull as expressed by state and local governments. Strategy and operations have been organized around this government-to-government pull. FEMA logistics and NORTHCOM and other federal players want to push as much as they can as quickly as they can to fulfill this pull. A previous FEMA Administrator is often quoted as crystalizing this strategy as, "Go Big, Go Fast." The full quote is actually, "Go Big. Go Early. Go Fast. Be Smart."

Analysis and Lessons Being Learned

In the midst of enormous and persisting challenges, water, food, and fuel supply chains in Puerto Rico demonstrated considerable – some might say, amazing – resilience. The speed, scope, and scale of both recovery and adaptation meant that within four weeks of landfall over 90 percent of residents were fulfilling fundamental needs through the strategic capacity of preexisting systems.

There was, however, no systematic process by which municipal, Commonwealth, or Federal authorities could be confident of this recovery/adaptation – or accurately map where and when the recovery/ adaptation was *not* happening – or strategically target public sector interventions to facilitate recovery/adaptation.

Instead, Federal, Commonwealth, and local authorities focused primarily on deploying an effective relief channel for mass feeding and other direct assistance to all survivors. As a matter of statute, policy, and strategy, this relief channel assumed the failure or near-failure of the preexisting demand and supply chain. The relief channel was organized to replace, not to supplement or gap-fill preexisting strategic capacity. It did not – probably cannot – have this capacity, but fortunately this capacity was not needed. The relief channel did deliver important water, food, and other assistance to hundreds-of-thousands of Puerto Ricans.

In contrast with contemporary demand and supply networks – Ana's Sistema -- the relief channel is a "push" function that only vaguely perceives consumer or System pull. The receiving government is the source of pull for the relief channel. The receiving government typically does not know the capacity, capabilities, or status of preexisting supply chains. On September 25, 2017, when the request for six million meals per day was generated very little was moving in Puerto Rico. But within three days of that request, commercial movements surged. Within three weeks the transformation of the preexisting demand and supply chain was dramatic. But these changes are – especially in the fog of crisis – not always obvious. As a result, the pre-determined relief channel push continued, regardless of its effective response to human needs or network effects.

FEMA professionals who had served or are serving in Puerto Rico – and many of whom are military veterans – occasionally say something like, "We are doing a messy job of saturation bombing when we need more effective precision targeting." Some FEMA professionals – and others – are in retrospect, especially concerned that the energy and attention given to "saturation bombing" could have been much better applied to filling other needs where there was insufficient preexisting strategic capacity. Blue Roofs, satellite communications, and fuel racks are often mentioned as examples.

Rapid assessment teams are deployed to impact zones. But their mission is often less to assess the status of preexisting supply chains and much more to determine where and how to direct the relief channel. There could be a process by which the relief channel is guided to where preexisting networks have failed. There could be a process by which the relief channel extends support to restoring key elements of the preexisting network, especially functional modules at the necks of hourglasses.

In Puerto Rico – as in any extreme event – several chokepoints were created or amplified. Post-Maria, the capacity and capability to push groceries recovered quickly. The capability to pull groceries with the PAN card (and other bankcards) was mostly lost. Once this chokepoint was recognized several, comparatively quick and inexpensive solutions were deployable. But the relief channel did not seem able to recognize – or respond to – this strategic opportunity.

In Puerto Rico – as in many disasters – fuel distribution emerged as a fundamental problem to be solved. As a matter of statute, policy, strategy, and operations, the "fuel mission" has mostly been defined as fuel for the relief channel. Significant efforts are made to avoid complicating commercial recovery. But little attention is given to helping preexisting fuel distribution capacity or capabilities recover or adapt. Again and again, long lines of fuel tankers form around the racks rather than making their rounds. Can this recurring pattern be effectively understood and operationally engaged?

How can the public sector develop sensing capabilities that will allow it to track and target where the preexisting supply chain's strategic capacity has failed or is failing? There is a potentially important role for local to national authorities to gap-fill and reinforce the pull and push capabilities of preexisting strategic capacity. Rather than behaving only as a relief channel, the public sector role can be reconceived as a strategic-adaptation function.

The experience in Puerto Rico suggests that this non-traditional role could be a crucial capability-multiplier for serving dense populations surviving an especially hard-hit and any extended period of critical infrastructure failure. Puerto Rico has demonstrated several strategic soft spots where non-recovery of preexisting capacity was experienced or threatened. Electronic Data Transfer, trucks and truckers, and fuel distribution were especially threatened. Are these – and other – threats exclusive to Post-Maria Puerto Rico or systemic? Based on the Triple Disaster, Superstorm Sandy, and plenty of other events there is evidence to support systemic implications.

Contemporary demand and supply networks are complex adaptive systems and, in many ways, common-pool resources with large numbers of stakeholders, where no one is in charge and, in most meanings of the phrase, no one can be in charge. But there are opportunities for key stakeholders to share understanding, strategic intention, and operational influence.

I appreciate the permission and cooperation of the CNA Corporation to reproduce this extended excerpt from "Case Study 1: Retail Resilience in Puerto Rico" (*Supply Chains and the 2017 Hurricane Season*) with modest edits. The complete case study and more CNA assessments of the 2017 US Hurricane Season are available at:

https://www.cna.org/reports/2018/01/supply-chain-resilience-and-the-2017-hurricane-season

Micro-Case 4: Demand Disruptions and Eruptions (Pandemic 2020-2022)

On December 28, 2019, a seismic swarm disrupted the grid, road networks, and more in southwest Puerto Rico. Given my experience on the island I was asked to provide a quick assessment of possible supply chain implications. While online working this assignment, I noticed reports of a "new kind of flu" in Central China. I added this to a long list of issues to monitor.

It was not easy to monitor. Early in the New Year I reached out to friends and contacts in China, Hong Kong, Japan, Britain, and the United States to learn what they knew. Not much. On January 6 the New York Times published an online report. The next day the report appeared on page 13 of the printed paper, including: "Symptoms of the new illness include high fever, difficulty breathing and lung lesions, the Wuhan health commission has said. No deaths have been reported but seven people are critically ill. On Sunday, the city government said they had ruled out as causes SARS, the Middle East Respiratory Syndrome (MERS), bird flu and the adenovirus."

On January 7 China's health authorities identified a "novel coronavirus" as the cause of the Wuhan outbreak. On January 11 China first reported a death directly tied to the virus. By mid-January cases had been confirmed in Singapore, Thailand, and Japan. On January 22 the Centers for Disease

Control reported the first laboratory-confirmed case of the 2019 Novel Coronavirus in the United States. On January 23 mass quarantine was imposed on the population of Wuhan and near-by.

On January 24, a coronavirus-related supply chain "disease" was the focus of this note to several clients:

> Hoarding has started in China. Hoarding will crash supply chains worse than most cyclones or seismic events. The experience of hoarding in densely populated areas is worth close examination. A few years ago, we did a US pandemic exercise and hoarding took-down the grocery supply chain in the mid-Atlantic almost two weeks before the pandemic wave really hit the East Coast. Now is the time for US supply chains to consider the emerging threat. Someday – sooner or later – we will face something similar. Just a few empirical principles worked out now could be helpful then.

On January 27 the World Health Organization reported 2798 confirmed cases worldwide, roughly 60 percent of these cases were in the province surrounding Wuhan. It was confidently assumed there were many-times more unconfirmed cases. There was much less confidence regarding the virulence of the virus. Images out of China were troubling. The lack of meaningful data out of China was of even greater concern, but at least 106 deaths had been credibly counted. Excerpts from a January 28 client note:

Measures intended to contain the disease have suppressed manufacturing, transportation, and other commercial activities in most of China... To date, impacts on demand and supply networks have been entirely the result of measures taken to control the virus, not a direct result of the virus or even the secondary effect of 2019-nCoV on the population. Official quarantine operations – combined with nervous buying and consumer hoarding – have effectively collapsed ordinary "last-mile" supply chains across much of the central Yangtze River Valley serving more than 55 million people.

While spot shortages of individual products are possible, overall US healthcare inventories should be sufficient for *normal* seasonal demand through late February. If Chinese manufacturing and/or transportation sectors experience extended disruption, the United States is most likely to experience systemic shortfalls in the supply of medical consumables, followed by selected medical devices, nutritional supplements, and generic drugs.

If the novel coronavirus becomes epidemic in the United States and *if mortality and morbidity rates for this virus continue to be modest*, [original italics] then the principal risk to demand and supply networks is likely to be unsustainable surges in demand reflecting consumer uncertainty regarding the resilience or integrity of local supply chains. This has already been observed in last weekend's surge in demand for facemasks in New York City.

Similar behavior has been observed in central China impacting the retail food supply chain. Nervous buying or hoarding tends to break-out in rather specific geographic – and population – clusters. If the underlying uncertainty can be quickly and effectively countered in the initial outbreak, this can amplify wider confidence in supply chains and serve to discourage further demand surges. But once any extended demand surge exceeds cycle-time of distribution capacity, retail shortages are inevitable, and retail shortages serve to inflame increased nervous buying and hoarding.

By early February I was receiving too many questions to answer each individually. Using daily summaries and weekly synopses I tried to integrate questions and responses. Following are several excerpts from a long February 4 note. The underlined bits were live hyperlinks. These references now appear in the research bibliography beginning on page xxx.

Chinese, US, and global supply chains are being stressed and strained by current disruptions. These disruptions will increase in the weeks ahead. How bad it will get is tough to determine – and may depend much more on our response to the disease than to the direct impact of the disease…

The potential implications for US demand and supply networks are varied. For example, many industry insiders are concerned that supply of Active Pharmaceutical Ingredients (APIs) on which many over-the-counter and prescription drugs depend will be disrupted. Apple could be hit by both demand and supply reductions Thousands of US firms depend on Chinese parts and materials. It would *not* be surprising to discover several examples of crucial components that depend on only one production cluster in China... or just one facility. To be clear, *channels* between China and the United States remain open. Chinese ports are operating. But the number of sailings, already reduced for the holiday, will be further reduced. Air traffic into China has been drastically reduced which also slashes so-called "belly cargo" capacity both into and out of China.

I have been focusing personal attention on medical consumables (e.g., gloves, disposable syringes, gauze...) and lower-end medical devices (e.g., infusion pumps, pregnancy test kits, catheters...) China is a significant source of flow for both of these product-categories. Soft-soundings with major medical goods distributors, hospital procurement officials, and other preexisting relationships suggest that in anticipation of the Lunar New Year most US institutional buyers had topped-off inventories in the second half of December or January. Given normal demand, my comparatively small personal network seems confident they will be okay through the end of February and even into early March. The flow of these lower-cost products is typically NOT Just-In-Time, so holding buffer stock is not unusual.

But demand has already been *non-normal* for consumer facemasks and clinical personal protective gear. Perhaps remembering the lack of supply during the 2014 Ebola epidemic, US hospitals have rushed to order more PPE. Suppliers have insisted PPE inventories are entirely sufficient for real needs, but are threatened by "nervous buying" (AKA bullwhip effect). As a result, there are several reports of medical goods suppliers restricting (allocating or rationing) institutional orders to no more than 125 percent of ordinary.

Of course medical consumables -- including masks and PPE -- are also needed to meet the surge in *Chinese* consumer and clinical demand. It is not at all clear that Chinese suppliers can catch up with Chinese demand -- not to speak of global demand. This Novel Coronavirus has, so far, demonstrated rapid rates of reproduction (more on reproduction from the New England Journal of Medicine).

In my *very* tentative judgment, the direct impact of the disease on supply chains is not possible to *reasonably* project until we have a much better understanding of lethality (*force* on target). If the Novel Coronavirus demonstrates low rates of lethality, then healthcare supply chains will still be seriously stressed, but other demand and supply networks should be resilient (if we can minimize consumer hoarding and other exogenous impediments on flow). One of my colleagues with long experience in the healthcare supply chain makes the point, "In terms of push, so far the virus itself is not the most

> serious problem. Most US inbound problems are the unintended consequence of actions to contain the virus." But if the Novel Coronavirus is both highly contagious and unusually lethal, then all major demand and supply networks are likely to experience serious, recurring, and sustained shocks. So, I am being not just tentative, but provisional...
>
> Complex Adaptive Systems -- such as high volume, high velocity demand and supply networks -- resist prediction, but they often reward strategic anticipation.

It is usually better to show than tell. But an accurate insider view of complex adaptive systems can be tough to find. The following is from the state-owned China Global Television Network (CGTN). I included this, with my bold blue exegesis, with the email quoted above. As I told the original readers, this outlines several classic issues of Supply Chain Resilience. I suggested that readers think about something like this happening to their place or enterprise.

Why an acute shortage of masks persists amid the coronavirus outbreak

By Yu Jing, Updated 12:08, 03-Feb-2020. Originally reported on CGTN (owned and operated by the government of China)

As the coronavirus spreads in China, everyone seems to be running short of facial masks. Pharmacy shelves were scooped bare. E-commerce sites see their stocks gone in seconds.

Even doctors battling against the virus had to recycle their masks due to limited supply. As fear of the virus strains supplies, mask factories across China cancelled their Spring Festival break and rushed to increase production. In its latest press conference on Sunday, the Ministry of Industry and Information Technology said that by Monday the daily production capacity of mask factories would bounce back to 60 percent of the figure before the Lunar New Year holiday.

[The gap between demand and supply is not estimated. But production remains 40 percent below normal. Demand is what percentage above normal? Demand is almost certainly some multiple above total capacity. Some clues below.]

Yet the acute shortage of masks persists. "In the past, only those who are frail or those under special working conditions wear masks. But now, everyone wants to wear a mask and what's more, they want to have a few extra to hoard," said Wang Yu, deputy head of a mask factory in Beijing who preferred not to reveal the name of the factory because he is not authorized to speak.

[Nervous buying or hoarding or any sudden, unpredicted cause of demand surge are often the greatest threats to Supply Chain Resilience. Once the hoarding cycle begins it is very difficult to reassure consumers, even when there is sufficient supply. In this case, supply capacity is probably not equal to current demand.]

His factory saw a huge jump in orders in late January. But due to a shortage of raw material supply during the Spring Festival holiday and travel control to contain the coronavirus outbreak, he cannot resume production as of now. [Contemporary demand and supply networks abound with interdependencies.]

While a lack of surgical masks are reported in hospitals at Wuhan, the epicenter of the coronavirus epidemic, the shortage of N95 masks, advised by doctors as essential for those who interact with their patients, is much more severe. [Some elements of flow are more important than other elements of flow, depending on many factors, but especially life safety and force on target.]

There is a pretty low skill threshold to producing surgical masks: It is a highly automated business that relies on machines to process raw materials. The difficulty, however, lies in the production of filters, the thing that enables N95 masks to filter out small particles from the air.

"There are thousands of mask factories in China, but companies that are able to produce high-end filters up to the N95 or KN95 standard, number less than 10," Wang told

CGTN. **[Behold a *bottleneck*. As the National Academies report recently highlighted, "The bottleneck can be understood as the point in a supply chain that limits its flow." And what is described is not just any bottleneck, but a preexisting systemic bottleneck.]**

Tianjin Teda Corporation is one of the biggest producer of filters in China. Around January 20, three days before the central China city of Wuhan was locked down, the company's order for a single day exceeded more than two million tons, almost an equivalent of its usual one-month's order. **[A demand (pull) multiple of at least twenty.]**

"We did not stop production at all during the Spring Festival break. We promised our workers three times their normal wages to get them back to work during the holiday," Hu Jun, chairman of Tianjin Teda Corporation, said in an interview with CGTN. **[Action was taken to increase *utilization* of existing capacity at the bottleneck.]**

Filters produced by his company can now sustain the production of seven million masks per day, 35 percent of the daily mask production capacity in China.

Liu Jie, vice president of a company based in central China's Hunan Province, which also manufactures filters, said her company resumed production on Wednesday, cutting the Spring Festival holiday short due to high demand from mask producers.

Though her company had stocks for some clients, she said the difficulty lies in transportation. "We now require our clients to pick up the materials because there is no way for us to ship the orders." Delivery companies, on the other hand, cannot handle such a huge sum of products, she added. **[This is an example of a *process* bottleneck for the face mask industry. It can also be considered a *capacity* bottleneck for the transportation industry.]**

On top of that, since some inter-provincial highways are blocked, raw materials need to be shipped by air, Wang, the mask producer said. "But the problem is, we are talking about tons of materials which cost of delivery by air would be exorbitantly high." **[These atypical costs are not sustainable. Suffering these costs for an extended period will destroy production ability. "Profit" is, in part, a key measure of network and system fitness. If current flow is not sustainable, much better to take mitigation steps as early as possible. In a crisis, does this tee-up a potential role for the Public Sector? If so, when and how should action be implemented? What preparedness is needed?]**

Teda Corporation, on the other hand, was one of the lucky few that managed to ship tons of filters via highways in the curtailed traffic system. That was because they received assistance from the municipal government when shipping masks to the quarantined city of Wuhan. **[An example of Public Sector action to reduce a process bottleneck.]**

Across China, all levels of central, municipal and provincial governments have vowed to assist producers of protective equipments in filling in the raw material supply gap, recruiting labor force and logistics coordination. A temporary redistribution system was also set up to ship production from major factories nationwide directly to the epicenter of the crisis in Hubei Province. **[Ditto, ibid]**

"As far as I know, almost all big mask factories are now responsible for alleviating the mask shortage for people in Wuhan and other regions of Hubei province," Wang said. "Major factories are responsible for production, not for sales."

On Sunday, the Ministry of Industry and Information Technology said a review of available protective equipment shows that there is still a large gap between the production capacity of factories and the surging demand from the public. By far, the need of Wuhan and other regions of Hubei Province should be prioritized. **[According to the National Academies report there are three kinds of bottlenecks: 1) Process, 2) Capacity, and 3) Utilization. Each can have similar results. All are present in the current situation in China. Capacity is often the toughest and most time-consuming to resolve.]**

The shortage of masks almost struck everyone by surprise in China. Before the coronavirus hit, the country was the world's largest producer of masks, accounting for 50 percent of annual production in the world. **[What are the risk implications of this sort of concentration? When a long-time**

US supply chain professional read this sentence, she wrote back to me, "Is this really a surprise, or could this shortage have been predicted? Is it truly a black-swan, or a predictable surprise? Is panic predictable? I'm not surprised by the shortages in China, nor by the current increased demand in the US."

The number of mask factories grew almost overnight as demand for masks to protect against PM 2.5 (**Palin note**: a kind of air pollution that has especially troubled China) surged in the early 2010s. Before 2013, China was home to 500 mask producers. That number grew to more than one thousand in two years.

But the mask industry was not in good shape in years preceding the coronavirus outbreak. As a war against pollution was declared, major polluters, e.g. steel factories, coal mines, and cement factories, were closed or required to adopt measures to curb pollution, and thus the demand for masks dwindled.

"We lost many clients during those years... and we have a really low profit margin," Wang said looking back to the past few years. **[Loss of network capacity.]**

There are signs that the shortage of masks is to be addressed. The government of Hangzhou announced on Sunday that residents can get up to five masks for free after reserving. The local government of Xiamen in East China's Fujian Province launched a lottery system for mask purchases. In Shanghai, residents can sign up to buy up to five masks. **[In many cases** this sort of rationing only reinforces the consumers sense of uncertainty and can actually increase consumer pull.]

Experts are also appealing to the public to save the N95 masks for medical professionals. Zhang Wenhong, head of the Shanghai medical team batting the coronavirus, said in an interview with CCTV that surgical masks are good enough for average citizens. "It is not necessary to wear a N95 for an average resident on the street," he noted.

Think about something like the above happening in your jurisdiction (in some ways *it is happening*). What would you want to know well-before the crisis emerged? Who would you want to know? Where would you focus your time, energy, and other resources? Why? What can you do today and tomorrow to be better prepared for what is described?

Never again did I see such a detailed, transparent, coherent report on near real-time domestic flows in any media outlet originating in China. Some Hong Kong media tried, but even they had a tough time penetrating the fog of obfuscation, propaganda, social media swings, and confusing outcomes.

Anticipation is often informed, even motivated, by analogies. How might the situation in China as described in the CGTN report resemble the emerging situation in the United States? What does demand and supply for facemasks in China tell us about demand and supply in general? What does this reference case tell us about specific options for our own analysis and action? What characteristics are shared? What characteristics are divergent? Given observations or experience of any potential analogy, what should we do or not do? Analogies can be treacherous. Bad analogies based on misperceived and inaccurate comparisons will mislead. But with better or worse outcomes, we are constantly scanning for and trying to make sense of potential analogies. Self-disciplined – and process-disciplined – engagement with analogies allows us to anticipate and mitigate risk. But in early February 2020 I found very few emergency managers or supply chain professionals inclined to embrace potential analogies with the "new flu" in China.

After an April autopsy we learned that during the first week in February Patricia Dowd of Santa Clara County, California died from covid. But as of February 6, the official count of known US residents with confirmed cases was only one dozen nationwide – with no fatalities. The official count in China was 600 dead and over 27,000 confirmed cases. What may seem obvious now, did not seem obvious then. The risk seemed too distant to take much action. Watch and listen – sure. But active preparation for similar outcomes in the United States seemed premature – alarmist – to most.

I did not want to sound like Chicken Little. But the analogies were more and more persuasive to me. Many of my communications – even written communications – began to deploy more personal pronouns and personal opinions. On

February 13 I sent a thousand-word email to several dozen US private sector executives and public officials:

> In several Chinese cities and Hong Kong and to a lesser extent in Singapore, (more) initial local confirmation of the epidemic prompted a surge in grocery demand. This consumer behavior was very similar to hurricane or blizzard preparations in the United States. Forty-eight hours after each confirmation, this behavior was much reduced and, in many cases, inventories were quickly replenished. The most effective way to discourage hoarding is to demonstrate that hoarding is not necessary because consumers can be confident of continuing supply.
>
> In most of China -- even in Wuhan, the hard-hit epicenter of the epidemic -- grocery flows have been able to fulfill core demand. But as the epidemic has persisted into its third (recognized) week, there is increasing evidence of uneven flow and persistent shortages, especially of fresh products.
>
> According to the Chinese government, the food processing sector has continued operating at a higher level than most other sectors. Roughly 95 percent of food processing facilities are said to be functioning (but at what capacity is not clear). As outlined in my February 4 note, strict travel restrictions were put in place after more than 160 million workers had already dispersed for Lunar New Year travel. The food processing industry has been caught up in this worker shortage.

So has trucking. There have been some – unreliable – estimates that sixty percent of Chinese truck drivers are not on the roads. Whatever the actual capacity reduction, it has been significant. Where truckers are delivering food they have been slowed by health check-points and, sometimes, by quarantine requirements.

Given these upstream constraints, it is remarkable that fundamental flows of food have been mostly sufficient to feed very dense urban populations. This has, it seems to me, been achieved by the interplay of three influences on the supply chain:

Demand Constraints: In an effort to reduce disease transmission, Chinese authorities have implemented an extreme strategy of social distancing. This restricts the number of household members who can leave their homes and slashes the frequency of grocery shopping. So, for example, in one jurisdiction one family member can shop for food every five days. More typically, in many jurisdictions one family member is allowed to shop every other day. This policy indirectly serves to reduce and even-out grocery demand which gives distribution assets a better chance of keeping up with demand. Food prices have also been increasing.

Supply Surge: Two examples: There has been a persistent private-public focus on keeping prominent market-leading grocery stores well stocked and constantly open… even while open-air markets are empty and smaller retailers are shuttered. Part of this relates to consumer confidence (next, below), but I perceive this is also part of a "surge" strategy to focus reduced trucking assets on fewer locations. Grocery stores (eg Hema) that also serve as Micro-Fulfillment Centers have been at the top of the list. Grocery and meal delivery services have significantly increased operations. There have also been recurring examples of police-escorting supply convoys and use of express freight trains to deliver bulk supplies into city centers.

Consumer Confidence: As noted above, ensuring that prominent supermarkets are rapidly resupplied has psycho-social value that state propaganda outlets have trumpeted again and again. In late January there were plenty of pretty pictures of people buying pork. I am told by locals that this was such an obvious ploy that it became the target of dark humor and the pictures have now mostly disappeared. But more broadly, there has clearly been sustained attention to reassuring consumers in both practical and symbolic ways that the grocery supply chain is a top priority. Finally, it is important to note that real demand has not changed and real supplies are not directly impacted by COVID-19. *Supply chain disruptions are the result of efforts to contain the virus, not the result of the virus itself.* Consumers have a substantive sense that food is available and some understanding of the distribution challenges.

Over the last week, however, food flows have clearly been less timely and effective in meeting demand. The restaurant sector has essentially shutdown, which has increased the pull for grocery. Friction accumulating across grocery and related networks has slowed and complicated push. Again, these are multifaceted dynamics, but in my opinion there are three particularly important facets:

Network Fragmentation: In late January local authorities across most of Eastern China began to impose increasingly strict social distancing structures: school closures, non-entry, restricted movement, multiple checkpoints, various forms of increased surveillance... In many ways, over the last week or so the original social distancing has morphed into a social-*isolation* regime that has significantly increased impediments to movement of any kind, including trucks carrying food. Wuhan was (is?) an especially important road-rail-and-river hub for China. Road and rail movement through Wuhan has been significantly reduced. Yangtze River traffic has been delayed but continues.

Reduced Network Velocity: This self-imposed fragmentation of social and transportation networks has altered the direction and destination of food flows (eg fewer open-air markets, more home delivery) and, especially over the last seven to ten days, has substantially increased the time required for long-distance transport (multiple checkpoints and other impediments). So... the fewer remaining trucks require much more time to deliver. According to everything I can see and hear, food supplies are entirely adequate. But the ability to distribute these supplies is much reduced.

Degraded network adaptability: Chinese authorities have attempted to mitigate these constraints by, for example, dispatching express trains from vegetable-growing Shandong province to major urban areas and releasing emergency stockpiles of frozen pork. But this military-style logistics operation cannot achieve the volume or velocity of the preexisting food distribution system. And as the grocery network depends on fewer retail nodes and many fewer trucks (well, really many fewer *drivers*), the ability of the network to flexibly and effectively respond to demand is incrementally reduced. Yesterday I wrote to some colleagues: "Entropy is accelerating across the entire demand and supply network." A bit melodramatic, I will admit; but it is what I have perceived -- especially this week.

On Wednesday, February 12 the central government began what appears to be a sustained effort to reintegrate and stimulate Chinese economic networks. According to the South China Morning Post, the President of China, "urged local authorities to refrain from taking excessive measures to curb contagion. 'We must correct these overreactions and extreme measures and avoid an oversimplified approach [such as] blanket closures or suspensions of business operations'." COVID-19 remains a serious threat. There is also an increasing threat of economic entropy. This tension is treacherous.

Retrospectively, I am not unhappy with this analysis – and pleased by the more urgent rhetoric. But there was not – yet – much response. More people asked to receive my emails.

There were some interesting teleconferences (I had not yet heard of Zoom). But very little action. During the second half of February three new risk analogies were delivered. The Diamond Princess cruise ship was overwhelmed with 700-plus cases and, eventually, more than a dozen deaths. The world watched as elderly clusters across Italy suddenly succumbed to covid contagion. On February 24 the BBC headlined, “Global Stock Markets Plunge on Coronavirus Fears.” Following is a long email sent on February 28. This was a “core text” that I personalized to several specific local, state, and federal public-sector decision-makers.

> This week I have had several informal discussions with grocers, grocery distributors, and truckers about covid-19. I perceive [name of recipient’s organization inserted] has an important role to undertake, sooner rather than later, to facilitate continued flow of food in case of quarantine and related impediments. Here is some of what I have heard:
>
> Grocery distributors are concerned about consistent and authoritative public health messaging that will allow their Distribution Centers to continue receiving inbound and delivering outbound. This especially relates to any required use of PPE or other non-standard food safety practices.
>
> Grocery retailers, grocery distributors, and truckers are concerned that truck drivers be given clear, consistent, and credible guidance on their personal risk and recommended

risk-avoidance behaviors. In many cases, it is not possible for truck drivers to deliver products and stay in their cabs. Trucking companies are concerned that even if messaging is credible and encouraging, many truckers will choose not to deliver in areas where quarantines or even less rigorous measures (e.g. school closures) have been implemented. There is no excess capacity in the trucking market. Each trucker lost will result in reduced flow of food and other resources.

Grocery retailers, grocery distributors, and truckers all report that school closures will have a constraining impact on continued supply chain operations. Grocery retailers seem especially concerned in this regard.

All of these supply chain stakeholders are concerned that interstate and (perhaps especially) *intrastate* impediments to the movement of groceries, medical goods, and other products be minimized as much as possible. Variance in protective measures by different jurisdictions will at least slow-down the supply chain. The more health-checks and other restrictions on flow, the more likely that truck drivers will choose to stop delivering.

Multiple health-checks and differentiated local quarantine practices fragmented transportation networks in China and significantly reduced supply velocity. If similar strategies are implemented in the United States, it would be helpful for hours-of-service, weight-restrictions, and other usual constraints on transportation to be waived to mitigate loss of velocity.

All of these supply chain stakeholders would value a national mechanism for resolving supply chain bottlenecks that emerge from local variations in public health policy or practice.

Many—*not yet all* --of these grocery retailers, distributors, and truckers perceive that there are important strategy and preparedness discussions that could be happening now. Early this week, all reported that there was mostly a lack of discussion and considerable uncertainty regarding this emerging threat. There seemed to be more private-private discussions happening by Thursday afternoon. Each of these stakeholders also pointed to other issues -- both urgent and chronic -- that continue to have greater priority… at least until actual disruption begins.

As you have probably seen, starting Monday Japan will close its schools until early April. This strategy of social distancing reflects an emerging consensus in the public health community that wide-area lockdowns in China have been fundamental to containing the disease. Given the hidden head-start of covid-19, especially in Wuhan and nearby, and given the limitations of China's public health infrastructure, I am not inclined to second-guess the decisions made in China. But we have all seen the unintended secondary and tertiary outcomes of this strategy, especially on bottlenecking of essential supply chains. In a long-term event, the secondary and tertiary effects of extreme social distancing will stress all supply chains, including food and medical goods. In China, as the scope and scale of local lockdowns increased, preexisting demand and supply networks were seriously degraded. In the case of similar behavior here, there is no reason to assume less severe outcomes in the United States. There are even reasons -- some outlined above -- to anticipate more difficult outcomes in the United States.

Late Thursday Governor Hogan of Maryland said that local schools and daycares should be prepared with contingency plans for potential long-term closures, communities should prepare to cancel or postpone mass gatherings and local businesses should be ready to adjust for possible work-from-home scenarios. Maryland is not alone. Grocery stores and Distribution Centers are not "work-from-home" environments. Below are excerpts of a note from a colleague in California who has been in discussion with county and state public health professionals and is concerned by a lack of systems-thinking in current plans (and non-planning). Given the number of possible covid-19 cases under observation, a California focus is not inappropriate. The *preemptive* lockdown of Camp Humphreys and other US military installations in South Korea is an interesting precedent.

> Much more could be reported, but after this week's informal conversations I am concerned by an absence of policy and strategies to ensure how food and other critical goods continue to flow if epidemic suppression activities become widespread. Food is a Just-In-Time flow. The impediments erected to suppress disease transmission could easily suppress the flow of food too.

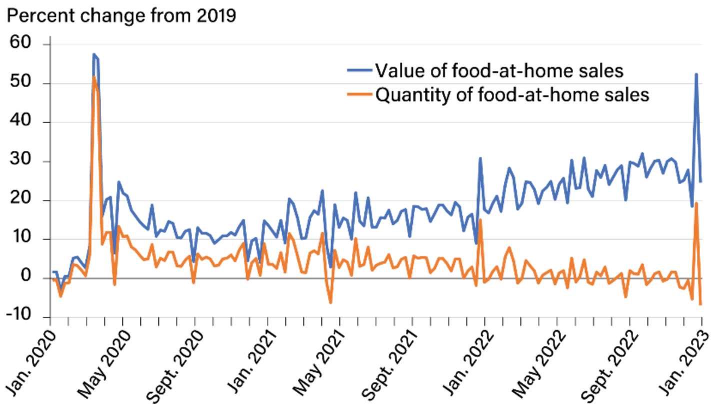
On February 29, 2020, Washington state announced the first then recognized covid-related death in the United States. The governor of Washington proclaimed a state of emergency. Each day in March arrived with rapidly growing case-counts. On March 11 the World Health Organization declared COVID-19 to be a pandemic. Temporary school closures began to be implemented in many places. Most colleges and universities shifted to online learning. Restaurant visits showed sharp declines. On March 13 a national emergency was declared in the United States. Many cities, counties, and some states banned large gatherings. On March 15 Ohio and Illinois announced the closure of bars and restaurants except for take-out and delivery. On March 16 seven northern California counties issue Stay-At-Home orders. On March 18 the State of California follows suit. New York and Illinois soon followed.

For the first week in March 2020, US food-at-home sales were about $4.5 billion, not so different than usual. In the second week sales were about $4.7 billion, closer to a Thanksgiving week. For the next two weeks grocery sales were well over \$6 billion each before settling just below \$5 billion per week. This surge was even more intense in certain places – such as New York City – and was more pronounced in specific product lines – such as rice, dried beans, and pasta. For the next two years US food sales continued well-above pre-pandemic levels and demonstrated much more volatile product and category shifting (see chart below).

In mid-March two factors were especially influential. First, Americans often spend about half their food dollars with restaurants, fast food outlets and other Food-Away-From-Home (FAFH) channels. As these closed-down, more was needed from – and more money was available for – the Food-At-Home (FAH) channel. Second, as the greater demand for shelf-stable foods suggest, there was also much more "pantry-stocking" in case of potential loss of food flows.

If you were living in the United States (and many other places) in March 2020 through the end of 2022, you experienced this uneven pull and push. Demand suddenly shifted from two high volume channels (FAH and FAFH) into one. Upstream capacity was organized around each channel. Redirecting that capacity was complicated. Percolation networks are not suddenly relocated. Even where content categories – e.g., meat, vegetables, and fruit – are the same quality, packaging, and size could be dramatically different.

Trends in weekly food-at-home sales by value and quantity began to diverge in early 2022



Note: Chart shows percentage changes in sales (dollar and quantity) from the equivalent week in 2019. The chart uses data from USDA, Economic Research Service's Weekly Retail Food Sales data product, which is subject to revision based on periodic adjustments in methodology underlying the proprietary data from Circana (formerly Information Resources, Inc. [IRI]).

Source: USDA, Economic Research Service Weekly Retail Food Sales data product using proprietary retail scanner data from Circana (formerly Information Resources, Inc. [IRI]).

Another analogy: the Ohio River is formed by the confluence of the Allegheny River and the Monongahela River at Pittsburgh. Each of these tributaries draw, broadly, on similar uplands, but from opposite directions. If the Monongahela was suddenly obstructed somewhere below Pittsburgh, it would be very difficult – even destructive – to try to quickly channel Monongahela flows into the Allegheny River channel. West Virginia's upstream capacity would persist, but without the Monongahela's discharge, Ohio River levels would drop. The drop would be even more precipitous to the extent that some were simultaneously trying to capture or redirect the Allegheny River's volumes.

From at least late January I tried to encourage several network participants to anticipate major changes in food, medical goods, and other flows such as that observed in China and then in Italy. I failed. The observations were often compelling. The mitigation opportunities were explicit. Many participants were interested. Strategic – and even several tactical -- analogies were relevant. Action remained anemic or simply absent. But as soon as demand shifted, supply started to follow. Pull did its job – much better than I did my job.

Where *capacity* to supply demand already existed, the network's adaptation was comparatively quick, creative, and persistent. High volume, high velocity US flows of canned soup (and related products) were robust in January 2020. Regulations, weight, and related costs tended to keep sources of soup supply within several hundred miles of high proportion sources of demand. When much more soup was suddenly being purchased, soup makers – both large and small across categories – added production time, reduced varieties, and otherwise tweaked throughput for amplified results. Expanding a near-by big flow by one-third was tough, but possible. There were trips, hiccups, serious falls, and a few utter failures, but an already big push could adapt to increased pull.

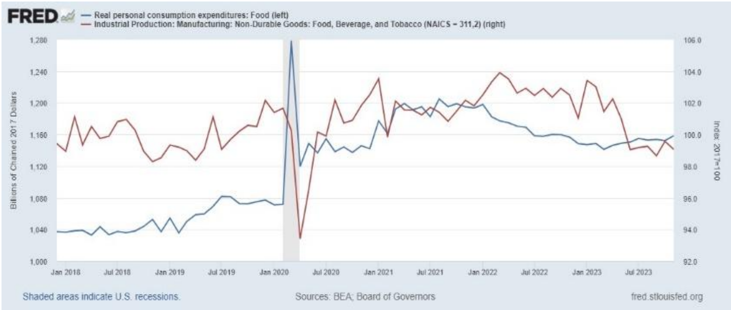
In January 2020 US production of N95 facemasks was about 1.5 million units per day. By late March this had increased to roughly 6 million units per day. Unfortunately, by the end of

March, US demand was at least five-times more and could be plausibly sized at fifty-times more. The largest-by-far pre-pandemic Giant Component for manufacturing all types of medical facemasks was in China, producing about half of global supply. The Organization for Economic Cooperation and Development has found:

> In January 2020, China could produce 20 million masks per day, which was insufficient to meet a total demand estimated at 240 million masks per day to equip health, manufacturing and transport workers. As a result of extensive efforts by the government and companies, Chinese production increased six-fold and reached 116 million masks per day at the end of February and possibly 200 million per day at the end of March (a ten-fold increase). The carmaker BYD, a joint venture between SAIC and General Motors, DaddyBaby (a manufacturer of baby goods), Foxconn (the company manufacturing iPhones for Apple), and China Petroleum and Chemical are all examples of companies that started to produce face masks at a large scale (i.e. more than 1 million per day).

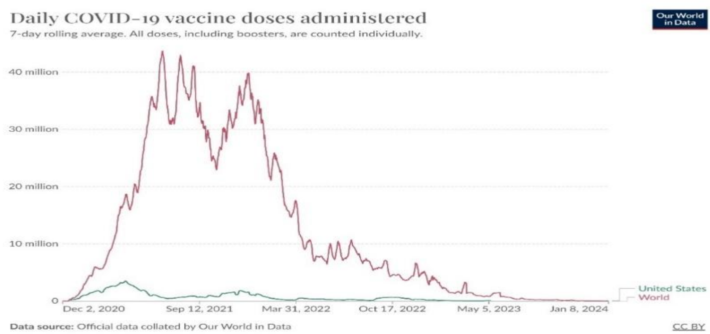
In January 2020 preexisting capacity for US soup manufacturing and distribution was about 3 million units per day, roughly twice the number of N95 facemask units made in the United States. Apples and oranges for sure, but preexisting demand and supply *capacities* are worth comparing. Starting in March 2020, US demand for soup expanded about 35 percent while demand for facemasks (and especially N95 masks) exploded by 500 percent or more. There are many other products similar to soup. Bandanas and self-separation were the principal replacements for facemasks.

Preexisting supply capacity matters. Distance matters. Potential replacement capacities matter. Inventories matter. But the supply of facemasks in March 2020 demonstrates the limitations of any network – any Giant Component – to fulfill sharply accelerated and exponential increases in demand. If capacity organized to supply recent demand (D) equals X, then with significant effort it is often possible to produce and distribute up to X^2. But as the D exponent increases, preexisting capacity seldom can keep up. D^5 does not magically generate X^5. China, the United States, and other nations made enormous investments to stand-up brand-new production and delivery capacity for facemasks, ventilators, covid testing, vaccines, and other crucial healthcare inputs. These investments benefited many millions. Despite the investments, more than 6.9 million people died of covid-related illness.



Stay-At-Home orders jolted demand and supply for food.

Facemask demand exploded/imploded with perceived covid risk.



Pull for covid vaccinations peaked when push potential was most constrained.

Micro-Case 5: Suddenly One Winter (EU Natural Gas Crisis: 2022-2024)

On February 24, 2022, the White House released six supply chain assessments that President Biden had ordered up to help deal with persistent pandemic-related friction. Late that afternoon I wrote some colleagues, "my first-blush impressions are less than enthusiastic. I don't — yet — see a coherent concept of demand and supply networks. Perhaps as a result, there does not seem to be much attention to policy integration across the six reports. I don't see much attention to meaningful private-public collaboration. I do see plenty of evidence for a government-centric approach. But – trying to read this turgid prose while the Russian military invades a neighbor — and answering lots of frantic questions — is not fair to the authors of these supply chain assessments."

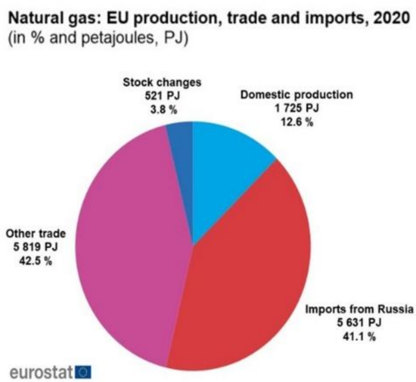
The dawn attack on Ukraine had long been signaled. Since December the United States and United Kingdom had released several declassified intelligence estimates warning of likely Russian military action. The invasion renewed Moscow's February 2014 efforts to constrain Kyiv's independence. Still, a full-scale shooting war in Europe was, if not quite a surprise, still a shock. Surfeit social media images of bombings, battles, and civilian casualties cultivated a surreal intimacy. Many in the United States and Western Europe could not imagine Ukraine successfully resisting Putin's punch.

No one asked me about geo-political implications. I was, however, receiving a barrage of questions about possible near-term supply chain complications. Here is one answer I provided as the Ukrainian Army's 4th Brigade was battling Russian airborne troops at Antonov Airport.

> Even before today, the Ukraine-Russia crisis was contributing to higher *petrochemical* and *raw grain* prices. There is also typically a price-multiplier between global energy costs and food costs… So, that will continue and, probably, accelerate with impacts on US fuel and food prices (but probably NOT much impact on actual US fuel and food supplies). Russia is a principal source of several strategic materials (e.g. *nickel*, *palladium*, and *aluminum*). But it is too early (at least for me) to confidently project primary, much less tertiary supply chain consequences. In terms of moving toward action, I think this is, so far, a "reduced resilience" story for the United States. There are many more supply chain implications for Germany, Poland, the Baltic States, and Finland (I hear mixed signals on the other Nordics). I can imagine potential implications for China flows, inbound and outbound, and that could have more direct US impacts. Barring something similar to this morning being repeated across the Taiwan Strait, I think these China-related influences will be fairly gradual… But we are dealing with plenty of known unknowns and even more deeply hidden unknowns.

In March 2022 Eurostat reported, "The EU depends on Russia for 24.4% of all its energy needs…The main origins of EU energy imports have changed in recent years, yet Russia has maintained its position as the leading supplier to the EU of all the main primary energy commodities: natural gas, crude oil and hard coal… Natural gas, a major fuel for electricity production and heating in the EU, represented 23.7% of the EU's gross available energy and had an import dependency rate of 83.6% in 2020 with imports of 400.6 billion cubic meters (bcm). The reliance of the European Union on Russian natural gas has increased over the last decade reaching 41.1% of gross available energy derived from natural gas in 2020, making it the fuel with the highest exposure to imports from Russia."

Before the invasion of Ukraine, selling natural gas was roughly as important to Russia's economy as assured supply of natural gas was important to the EU economy. In 2021 Russia's exports totaled almost $490 billion of which $54.2 billion was generated by pipeline-pushed natural gas, mostly sold into European markets. The mutual interest embedded in this commercial exchange was over-



valued in terms of geo-political risk mitigation. Many Europeans perceived that Russia would avoid rash behavior that might upset this perpetual cash-flow. Being a good customer of Russian gas was often treated as a convenient security guarantee for EU member states and even Russia's nervous neighbors. Meanwhile, many in Moscow assumed that with half or more of EU grid power depending on its natural gas, the European Union – and European members of NATO – would offer muted reactions to most measures undertaken in Russia's sphere of influence. Being a reliable supplier of natural gas was seen as reinforcing Russia's decayed Great Power status.

If anything, this recent mutual confidence in the natural gas connection amplified European alarm at the invasion even as it muffled Moscow's comprehension of changed context. Putin's "special military operation" could not depend on the same neglect given previous actions in Armenia, Azerbaijan, Georgia, Eastern Ukraine, and Crimea. Just two weeks before the invasion, German President and former Foreign Minister Frank-Walter Steinmeier strongly defended construction of Nord Stream 2 (see map below), calling this pipeline, "one of the last bridges between Russia and Europe... I believe that burning bridges is not a sign of strength." After the invasion Steinmeier confessed, "My holding on to Nord Stream 2 was clearly a mistake... We held on to bridges that Russia no longer believed in and that our partners warned us about... My assessment was that Vladimir Putin would not accept the complete economic, political, and moral ruin of his country for his imperial mania — there, like others, I was wrong." Shock was reinforced by shame. Urgent efforts at political and practical redemption followed. Just four days after the invasion, EU energy ministers met in Brussels. Among many other actions:

> Ministers also analyzed various possible scenarios for the coming weeks and months, in order to anticipate the potential difficulties that could arise and verify the Union's ability to overcome them. With regard to gas supply, coordinated action by the Member States and the Commission should make it possible to maximize supplies from outside Europe, particularly in terms of LNG, by strengthening contacts with producing countries and by adapting if needed our infrastructure. Ministers also reviewed Member States contingency plans to ensure a continuous supply of gas, protecting consumers in case of supply disruption. Member States agreed to continue working on contingency planning to be activated in case of need and to coordinate preparation for next winter.

As the winter war continued into Spring, I watched with surprise as large quantities of Russian natural gas still flowed west. In an April 7 note, I reported, "the TSO pipeline continues to deliver Russian natural gas west across Ukraine. This week in 2021 the flow rate was just under 201,000 million cubic meters. Right now, the flow continues at just above 183,000 million cubic meters. War or a warmer spring or price-induced lower demand? I don't know. It would be easier to explain zero flow."

One month later, on May 7, I felt more confident in my observations and interpretations. “Russia’s natural gas suppliers continue to pay Ukraine’s pipeline operators to transport product to paying customers farther west. Bookings and flows have roller-coastered, but recent volumes often remain within range of early 2020 and most 2021 levels (more from Reuters and S&P and NYT). Russia’s oil outputs have been harder hit by Western sanctions (more from the BBC). But at the right price, buyers can still be found. Quick price hikes for global fossil fuels following Western sanctions have been contained by China’s economic slowdown… and the potential of lower global demand (more). More stubborn demand equals more stubborn supply. Less stubborn can also generate symmetries.”

Despite war-related complications and occasional diversions, stubborn demand continued to pull significant supply down the pipelines all spring and summer. This buying behavior reinforced Putin’s cynical calculations regarding Europe’s dependence on Russia’s energy flows. This selling behavior gave Europe more space and time to find alternative flows. If Ukrainian military opposition had quickly collapsed and a Putin-friendly regime had been installed at Kyiv, perhaps Moscow and Brussels (Berlin, Budapest, Paris, Prague, and even Warsaw) would have continued to dance along these natural gas bridges into post-war accommodation. But as Ukraine not only resisted, but persisted with creative courage, most Europeans began urgently seeking new bridges and better dance partners.

The most important gas pipelines in Europe

Source: European Network of Transmission System Operators for Gas BBC

As fierce fighting continued into summer, the old bridges continued to carry flow, but volumes were reduced. New natural gas channels struggled to connect and replace what was no longer arriving from thr east. On July 21, 2022, I outlined the then current context:

> This morning **natural gas is flowing again in the Nord Stream 1 Pipeline**. This is a principal channel for natural gas from Russia to Western Europe. The pipeline had been closed for usual summer maintenance. There was, however, concern that future flows could be held hostage related to the war in Ukraine (more and more and more).

According to Reuters, “Nord Stream 1 transports 55 billion cubic metres (bcm) a year of gas under the Baltic Sea and has been offline since July 11… A spokesperson for Austria’s OMV said Gazprom signalled it would deliver around 50% of agreed gas volumes on Thursday, levels seen before the shutdown.”

Depending on demand and availability of other sources, **natural gas typically provides between one-fifth and one-quarter of European Union grid generation**… Over the last two weeks, reduced wind and heat-related high demand have increased natural gas draws. On some recent days natural gas has provided nearly one-third of EU generation.

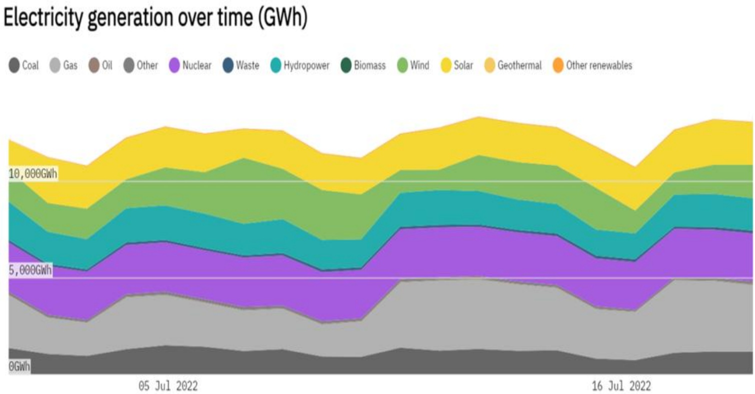
Despite the temporary shutdown of Nord Stream 1 and strong demand, **European natural gas inventories have not** (yet) **fallen** during July and storage domes are about 65 percent full, ranging from a low of 42 percent in Bulgaria to 100 percent in Portugal. France is at 72 percent. Germany’s natural gas inventories are currently measured at 65 percent full.

According to an S&P report on German natural gas purchases, “The share of Russian gas deliveries averaged 55% in the past, but this fell to 26% by the end of June,” the [German economics] ministry said, adding that last year Russia supplied 46 Bcm of gas to Germany. The lower share in June is a result of Russia’s Gazprom cutting supplies through the Nord Stream pipeline to just 40% of capacity in mid-June, citing issues with maintenance at a key compressor station. The ministry said the claims of technical problems was a "pretext"… Germany currently does not have the infrastructure to directly import Liquified Natural Gas (LNG) (more).

The natural gas network crossing west from Russia through Ukraine is operating at less than half its 2020 capacity and flows. Most recent deliveries are to Veľké Kapušany, Slovakia, with Hungary a distant second-place recipient.

The prospect of natural gas shortages during a war-torn European winter has increased the **need to maximize inventories and diversify channels and sources**. US LNG exports to Europe have been lower than expected partly due to the fire-related loss of the Freeport LNG terminal in early June. This is usually the second largest of seven US LNG export facilities. But other LNG operations are exporting at full capacity (more). Loss of Freeport has also meant lower than otherwise US natural gas prices. Without this, current electric rates in heat-ravaged Texas (and elsewhere) would be even higher.

So obvious it is barely more (or less) than nagging, but still: Concentrating flows to fulfill demand usually enhances efficiency and always concentrates risk. The most beautifully planned bottleneck is one surprise short of becoming a chokepoint.



European Union Electric Power Generation by Source July 1-July 20

During the second half of 2022, as Russia and Ukraine fought over Kherson, Luhansk, Mykolaiv, and elsewhere, a struggle was also underway between demand and supply. Which is more powerful? One of the most common and potent cognitive biases is loss aversion. Most humans in most circumstances give much greater weight to potential loss than potential gain. Putin played with his ability to push or *not* push natural gas into European markets in an effort to influence EU and NATO support for Ukraine. Meanwhile Europeans deployed their wealth and effectual demand in an effort to mitigate prospects of current and future Russian threats. In mid-2022 it was not yet clear if fear or hope, push or pull would prove stronger. On July 27, I wrote to clients:

> President Putin is depending on decadent demand. He is depending on European consumers and bourgeois politicians to succumb to high prices and chilly room temperatures. Putin has restored General Winter to a

prominent place in Kremlin councils. He hopes this summer's temperature extremes will return to Europe in dramatic winter garb. January is Berlin's coldest month with an average low of 29°F and high of 38°F...

Last year more than 40 percent of EU natural gas consumption was supplied by Russia. Since February 24 this proportion has plummeted. Flows vary by season. I'm not confident of a current comparative statistic. But several credible sources (here and here and here) indicate that Russia's EU market share for natural gas has been reduced by at least one-quarter, maybe as much as one-third. But, once again, dependence on Russian flows differs considerably by region. Hungary, Slovakia, Italy, and the Czech Republic are much more exposed to reductions in Russian flows than other EU nations.

Europe has significantly increased imports of non-Russian LNG. In June for the first time, US LNG deliveries to Europe exceeded Russian pipeline deliveries (more). The US would almost certainly be exporting even more if the Freeport LNG facility was still operating (and price-pull could be found). Qatar and Algeria (more) are also increasing LNG flows to Europe (more). As of July 25, EU natural gas domes are about two-thirds full.

Yesterday, July 26, the European Commission announced **decisions intended, "to reduce gas use in Europe by 15%** until next spring. All consumers, public administrations, households, owners of public buildings, power suppliers and industry can and should take measures to save gas. The Commission will also accelerate work on supply diversification, including joint purchasing of gas to strengthen the EU's possibility of sourcing alternative gas deliveries." According to S&P, a significant proportion of this reduced consumption may also be teed-up by price-driven reduced demand:

A 15% voluntary gas demand reduction target aligned relatively closely with a Platts' estimate of demand destruction due to high prices. Gas demand in Northwest Europe would fall by 13% between August 2022 and March 2023 compared to the five-year average demand for the period... Based on its TTF price forecast of Eur125-140/MWh, demand would be reduced in the power sector through maximum coal and oil switching, while industrial demand is forecast to drop by 15%.

President Putin has cut back Russian natural gas flows to Europe. He has not cut off these flows. As long as any Russian natural gas is going, this gives him potential leverage to cut further or promise increases. The cuts so far are enough to cause European economic (and political) friction (*and* to significantly increase prices being paid for what is delivered). Putin perceives that time is on his side. Maybe the Atlantic hurricane season will wallop US LNG exports. Maybe General Winter will descend on Amsterdam to Warsaw with the coldest temperatures in two centuries.

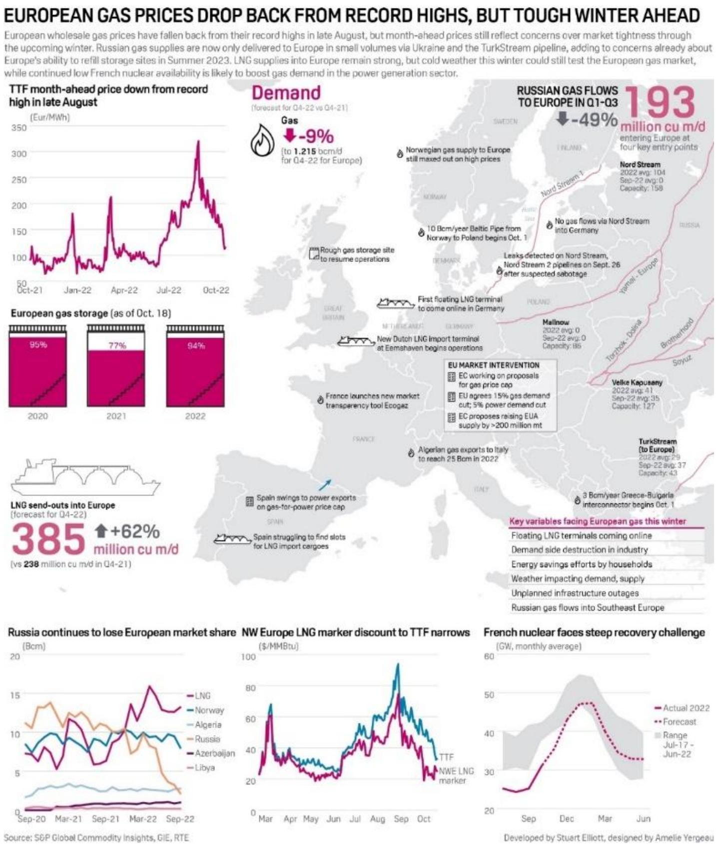
> He is confident that contemporary European consumers — and voters — are effete, weak, self-indulgent, and can eventually be distracted from any concern for Ukraine, much less what might come after Ukraine.
>
> The sharp and mostly unified NATO (plus) response to the invasion surprised Putin. But it now seems clear enough (*to him*) that this was just reflexive sentimentality. With the help of some snow and ice, his debauched neighbors will, he now expects, turn against their current political leaders who will then turn to him to restore flows...

These thoughts were pushed out about 0600 Eastern Time that Wednesday morning. Natural gas prices were already moving higher. Over the day they continued to gain. According to that evening's Financial Times: "European gas prices jumped higher on Wednesday after Russia followed through on its threat to further reduce supplies to the region, increasing the risk the continent could face shortages in the winter months. Gas prices rose as much as 13 per cent on Wednesday as flows on the Nord Stream 1 pipeline were cut to just a fifth of normal capacity." (More and more and more.) But by mid-day Thursday European natural gas prices had eased as reports were received that flows from Russia were, in fact, still pushing west.

The battle for the winter-still-to-come raged all across that super-heated August. During the second week I wrote, "Natural gas storage facilities in the European Union are now

over seventy percent full. Inflows have been well above normal for Spring/Summer since the end of May. France is at over 80 percent, Italy about three-quarters, Germany at the EU average. Austria, Hungary, and Latvia are closer to 55 percent (more). The (very high) natural gas benchmark price at Rotterdam has eased just a bit. High temperatures this week — increasing electricity demand — will not allow much near-term progress. Off-season natural gas demand (and prices) could also surge if coal deliveries to power plants along European rivers are disrupted by drought and falling river levels. Winter is certainly not the only threat. But winter is surely coming. Very few grasshoppers are seen in European capitals this year.

On August 12 S&P Global quoted a German gas-trader, "Even with full storages it could get difficult if winter gets cold or Russia cuts further." In the same report other market insiders argued, "We won't run out… no commodity ever runs out… it's all a matter of pricing now… the gas shortage will just be replaced with extreme price highs." Another European gas trader, also highly skeptical that Europe will run out of gas, said that "as storages continue to fill, the market should start realizing that the winter is looking less and less scary… as long as it doesn't turn out very cold." During an August 11 news conference, German Chancellor Olaf Scholz said, "We'll be in a situation… where it might be expensive to get gas, because of the state of the global market, but we will always get enough." (more and more). He was right. The Chancellor could not be sure he was right, but the next two years confirmed his fond hope and earnest expectation. As late as October 2022 S&P Global headlined (see below), “European Gas Prices Drop Back from Record Highs, but Tough Winter Ahead.” It ended up much warmer than President Putin or General Winter had been hoping. Pull beat push. Demand dominated supply.



It was a tough fight with an uncertain outcome. But in 2022 and since Western and Central European pull has had several strategic advantages over Russian push. Since 2015 global volumes of Liquified Natural Gas – transported by ship – have expanded by about 60 percent. In 2022 global demand for LNG was softened by slow East Asian recovery from the pandemic. If Europe was ready – and able – to pay more, suppliers were ready to fill where Russian flows were falling.

On September 14 I responded to questions about natural gas price volatility with, "Nordstream 1 is now closed (Nordstream 2 never started). Natural gas continues to flow west from Russia through Ukraine to Velke Kapusany then farther along (more and more and more). Current Natural Gas inventories in Europe range from a low of about half-full in Latvia to two-thirds full in Bulgaria to more than 90 percent full in Britain, Denmark, France, and Poland. The **EU average for natural gas in storage is hovering around or above 85 percent** of available containment." Strong demand to build European winter inventories of natural gas resulted in price increases that attracted more flow. But after a September 28 spike, prices have mostly fallen ever since.

October 2022's warm weather reduced typical demand for autumn residential heating. Combined with (a not unrelated) economic slowdown, high prices reduced industrial demand for energy including natural gas. Prices then started falling with demand. It got so bad – good? – that, several LNG vessels anchored off European LNG ports waiting for higher prices. According to one natural gas trade, “If one single idling vessel discharges its cargo, the price will immediately collapse by affecting the other cargoes on the queue and this domino effect is so painful in terms of opportunity cost.”

Consider the price patterns shown in the chart below. Constraints on preexisting push caused price increases. Higher prices then pulled more and alternative flows. When demand is more need-based than want-based and need-based demand can be effectually expressed (when pull can afford to pay the price), then *if flow is available*, push will find a way to connect supply with demand. Exceptions can be found. But the power of pull should not be underestimated.

On January 1, 2023 Europe’s second week of winter began with Frankfurt breaking 60 degrees Fahrenheit. Autumn in Paris (and Berlin and Amsterdam) had been remarkably mild. The EU consumed one-fifth to one-quarter less energy than usual. EU natural gas storage facilities were more than 80 percent full. President Putin’s plan to weaponize Western Europe’s winter did not go well. On that New Year’s Day even Kyiv was in the upper fifties Fahrenheit.

Commonalties across the Five Cases

Pull found push for new sources of natural gas flows into Western and Central Europe. Pull found push for preexisting food flows serving Puerto Rico. Pull found push for food flows across Tohoku—once the security perimeter was removed and preexisting push capacity could operate. Pull and push for fuel were never far apart in the aftermath of Superstorm Sandy or Puerto Rico but both needed electricity and enough tanker trucks to complete the circuit. Early in the pandemic, pull for facemasks found – and overwhelmed – push capacity. It took considerable time for constrained push capacity to effectively flex and stretch into such a suddenly disproportionate expansion of pull.

Concentration

People and products cluster and concentrate where varied paths intersect. As preferences play-out, if cluster-size grows, networks often accumulate functional characteristics that facilitate increased volume and movement at greater speeds in specific directions. Bridges are built. Prior to the bridge, there may be several well-used fords, none of which have any persistent advantage over another. But the comparative advantage offered by the bridge results in many prior paths being mostly abandoned. Recognizing this convergence of travelers, various services emerge around the bridge – or port or pipeline or more – creating even greater comparative advantage. Overtime preexisting paths at considerable distance from the bridge tend to turn toward it and the entire network gradually increases its dependence on the bridge.

These nodes—the swelling of demand and/or supply at a particular place—often facilitate flow: with markets, financial brokers, transportation resources, and other services to direct and accelerate movement. In some cases, these nodes become population centers, places of wealth and their own significant sources of demand, all of which reinforce pull across the network toward the node. Fuel capacity at Linden, New Jersey facilitated the economic and population growth of metro NYC – and visa-versa.

As mature, high-volume, high-velocity networks achieve scale, there is a persistent pattern of a small number of nodes taking-on an outsized proportion of flow. Over time the flow of people and products self-organize around a preferred set of paths and nodes. (This can be called percolation, making an analogy to how fluids find/create new nodes within and paths through porous media.) Flow tends to concentrate—we might say, flow tends to pool—in places with a depth of demand and the ability to influence the velocity of flow. At the macro-level great urban concentrations—New York, Los Angeles, Tokyo, Shanghai, London—attract and accelerate flow of demand and supply. High volume demand tends to transform natural percolation into engineered permeation, channeling pathways between nodes across a wide landscape.

Tohoku benefited from proximity to Tokyo's capacity concentrations. Once grid power was restored to the cluster of fuel racks near Linden the post-Sandy "fuel shortage" was suddenly solved. The supply chain cluster – concentrated capacity – at the Port of San Juan and near-by Bayamon demonstrated amazing resilience in the aftermath of Hurricane Maria. The distance between global demand for facemasks and (overly) concentrated capacity for facemask manufacturing in China was a tough problem early in the pandemic, as was the absence of high-proportion Giant Components anywhere outside China. Fortunately, there are widely distributed Giant Components for natural gas and other sources of energy. Western and Central Europe were able to attract push from these alternative capacity concentrations and transportation modes when Russia's flows were recognized as unreliable.

Betweenness

San Juan is open to the world. But San Juan is connected to the world through a rather small set of ports. The value of San Juan's shipments in and out of Jacksonville, Florida is greatest by far. Both ports sit between enormous pools of supply and demand. Most paths connecting Puerto Rican supply and demand pass between both ports. (There are network science methods for measuring "betweenness".)

Both Jacksonville and San Juan ports demonstrate the structural predispositions of high volume, high velocity demand and supply networks to assume hourglass characteristics. Linden and nearby evolved into a similar structure. In New Jersey, Puerto Rico, and almost everywhere, fuel racks and tanker trucks are crucial functional modules at the neck. Disposable-medical-goods clusters in Shandong and Guangdong have similar characteristics. I am not as well-informed regarding the natural gas pipelines terminals at Velke Kapusany. But I bet hourglass characteristics are prominent.

Large and widely distributed sources of demand pull large and widely distributed sources of supply through very narrow necks (or waists, both terms are used in network science literature). Kaeser M. Sabrin and Constantine Dovrolis, network scientists at Georgia Tech argue, "the hourglass effect should allow a system to accommodate frequent changes in its sources or targets (i.e., to be able to evolve as the environment changes) because the few modules at the waist "decouple" the large number of sources from the large number of targets. If there is a change in the inputs (sources), the outputs do not need to be modified as long as the modules at the waist can still function properly. Similarly, if there is need for a new target, it may be much easier (or cheaper) to construct it reusing the modules at the waist rather than directly relying on sources..."

Similar patterns repeat fractal-like across various networks. Fuel terminals with a rack become nodes with a high "betweenness" score. The rack itself is one of many flexible modules at the neck. More and more connections link with bigger and bigger nodes. Container ships, maritime ports, intermodal yards, distribution centers, pipeline networks, and all their cousins include modularized functions—receiving, storage, discharge, trucking, power, personnel, capital, etc. – that can be applied to a wide variety of inputs and delivered to many different targets across time and space.

Three days after Russia invaded Ukraine the German government announced expedited construction of three LNG terminals, the first of which began operating before the end of 2022 and the other two in early 2023. The jetty, dock, regasification units, storage, pipelines, and more form another neck in one more hourglass embedded within several other hourglasses that together form the network by which flow is facilitated over time and space. These are connections that can be mathematically measured by "betweenness" and other aspects of "centrality."

Bottlenecks and Chokepoints

An hourglass or potential hourglass or once-upon hourglass is where two bottlenecks join. If the bottleneck separates from either supply or demand it becomes a chokepoint. Once separated the bottleneck is unable to send signals (pour its contents) or receive signals (fill its void). Something is impeding flow. In many ways all five of these micro-cases are about fixing bottlenecks and restoring hourglasses. Bottlenecks are a recurring feature of demand and supply networks (and other natural and engineered systems). Even on the best days, impediments—accidental, structural, or intentional—emerge across networks. Chokepoints do not always emerge at the neck of an hourglass, but when they do, the impediment or separation has amplified effect. This begs the question: given the risk, why do many demand and supply networks display hourglass characteristics and form hourglass-similar spatial silhouettes?

To persist with the analogy, narrow necks allow bottles to be more accurately poured and assist in keeping unwanted bits out of the pour. Hourglass structures emerge in demand and supply networks to facilitate speed and accuracy of flow—and to contain costs. These are essential components of comparative advantage in any real-world network.

The functional modules created to facilitate flow and contain costs at the neck of an hourglass—such as cross-docks, fuel racks, and digital financial transactions—can be effectively deployed across a wide range of sources to serve a diverse set of targets. Entirely novel sources (new products) can often be delivered to previously non-engaged targets (new customers) by the very same modules. While functionally flexible, this is also an inherently conserving system. Any product or customer that cannot be served by some version of existing functional modules is unlikely to be well-served.

Fundamental changes in functional modules can have revolutionary impacts on the entire network. For example, shipping containers such as those on the *Ever Given,* have radically transformed the topology of global trade as much or more as the emergence of steamships. After 5000 plus years of break-bulk shipping, in the last fifty years this "new" functional module has increased the speed and accuracy of flow while containing per unit costs for many sources and targets (as well as contributing to the disappearance of weaker—or just smaller—network participants).

Given the significant network effects of functions concentrated at the neck of an hourglass structure, it is not surprising that serious consequences unfolded from loss and diminution of module capabilities after the Tohoku earthquake, Superstorm Sandy, Hurricane Maria, and the outbreak of war between Russia and Ukraine. Russia scooping content out of the hourglass also reduced flows. In the case of medical goods manufacturing early in the pandemic, we started with too few hourglasses, often too far away, and not nearly large enough to scale up quickly to whole-planet explosive demand.

In all five of these cases, I am surprised the consequences were not much worse. The worst case for adaptive flows emerged from the absence of preexisting capacity to fulfill explosive new demand for pandemic-related medical goods and pharmaceuticals. Otherwise, preexisting capacity consistently proved adaptable and persistent; in a word:

resilient. According to some network scientists, network resilience can be explained by characteristics of the modularized functions at the neck of hourglass structures. The structure itself *constrains content* and in the process *deconstrains capacity*. Self-restraint strengthens potential self-expression under duress – when the neck survives.

Research from biology, ecology, chemistry, information sciences, and more have found recurring examples of constraints-that-deconstrain. Organic networks emerging without human intention often assume hourglass structures and feature functional modules performing behaviors analogous to that we see in demand and supply networks. The human heart is a set of modularized functions at the neck of the circulatory system's hourglass structure. Cardiac functions constrain, even as they enable, empower, facilitate and in these ways deconstrain human capacity.

Chokepoints can emerge almost anywhere in a network. But chokepoints – network aneurysms — involving functions at the neck of an hourglass structure tend to have amplified effects. Broken necks will often have catastrophic consequences. Recognizing this vulnerability and knowing how to ease the constraints (and reinforce functions that deconstrain) is a very helpful skill.

Preexisting preferences can evolve into well-anchored patterns. Many high volume, high velocity networks are predisposed to concentration. Concentration of flows supports greater volume and, usually, greater velocity of flows. The more volume available, the higher proportion of network percolation. Large-scale, fully percolated networks usually spawn densely connected Giant Components.

The tighter connections within a Giant Component (and between Giant Components), the greater capacity for potential flow – and the more risk of flow impediments cascading across the network too. The most fully percolated networks feature multiple hourglass structures replicated fractal-like at every stage of demand and supply. Functional modules at the neck of each hourglass interact to both constrain and deconstrain local flows. When network flow is seriously disrupted, look for the most influential concentrations, the hourglass structures serving those concentrations, and the functional modules at the neck of those hourglass structures. You will almost certainly find how to fix or mitigate the cause of impediments.

Assessing and Advancing Fitness

Months after Maria I was in Puerto Rico talking to a colleague who had been deeply involved in the earliest response decisions. He said, "I need some way to get a quick, accurate read on supply chain fitness or non-fitness. I don't need—and don't have time for—an MRI. But I sure need to know about anything that is interfering with breathing and heart-function. Where is the bleeding? Where should I focus? Where am I not needed?"

The toughest need to fulfill in Puerto Rico was increased fuel distribution capability. Given ongoing demand for generator fuel, there were not enough tanker trucks and drivers to move product from supply nodes to demand nodes with sufficient frequency. What was not needed in most places was more food. As with fuel, there was a challenge moving food from supply nodes to demand nodes (partially because of the problems with fuel distribution). Unlike fuel, in most places there was no increased *need* for food (demand is a different story). But especially in the first two or three weeks there was no credible process for anyone to know what was happening or not happening. Diminished downstream flows were assumed to reflect reduced upstream flows. Midstream "necks" are seldom considered.

With congestion, disruption, or destruction at the neck of the hourglass in demand and supply networks, one frequent symptomatic result is consumer hoarding. We see hoarding in all five micro-cases. Supply uncertainty tends to prompt unsustainable surge in demand, which further disrupts, even degrades the network. The sooner that survivors see credible signals the preexisting supply chain is recovering—the sooner hoarding will stop. Rationing is a clear signal that the supply chain is not functioning near normal. Rationing spurs hoarding. Moreover, in many cases the process of rationing itself disrupts network flow, as it did with retail gasoline and diesel in the first several days after Maria. Once hoarding begins it can easily become a vicious cycle.

In Puerto Rico several factors were crucial to re-establishing network equilibrium after Maria. The persistence of incoming flows of fuel and food was fundamental. If the maritime bridge or the Port of San Juan had been seriously impeded, supply chain recovery would have been much more difficult and could not have been sustained. The hourglass did not shatter. The neck did not break.

The early delivery of additional fuel tanker-trucks was crucial. This expanded key functions at the neck of the hourglass. Deployment of electrical generators for the water system was as important but would have been meaningless if fuel distribution capabilities had not expanded to fulfill the needs of these and thousands more generators.

The functions of the human heart are regulated by the autonomic nervous system, a largely unconscious set of bio-chemical feedbacks that connect the heart to many other body functions. Many large networks feature a pattern of complex self-organization and emergent coordination among largely autonomous agents. Such behaviors are labeled stigmergic or sematectonic or as instances of swarm-intelligence. Depending on the agents and systems involved, the mechanisms of feedback and coordinated action can be dramatically different. But what these phenomena tend to share is a persistent pattern of signaling that prompts increasingly self-similar and symmetrical behavior by a significant proportion of the autonomous agents, leading to observable changes in network behavior.

Especially at scale, complex demand and supply networks depend on stigmergic coordination. Days before a hurricane hits the North Carolina coast, thousands of trucks increase deliveries along and through Interstate-95. In the 48 hours before the hurricane arrives thousands of trucks shift west to Interstates 85 and 77. No command is given. No network-wide control exists. But shared signaling prompts shared action over a wide area. When war began in Ukraine, the German government did give the command to build three new LNG terminals. They could not command more LNG tankers to show up. But long before the terminals were completed more and more LNG tankers set sail for Western Europe, autonomous agents responding to various feedback shifted direction and surged supply.

It is not difficult to find major nodes in demand and supply networks. Some links—such as high traffic truck routes, maritime lanes, and pipelines—pop-out. With careful observation, hourglass structures can be discerned, especially at obvious pinch-points including ports, big bridges, and mountain-passes. It requires considerably more care to determine the size, direction, and comparative value of flows between any specific set of nodes.

The comparative value of flow-as-flow across the whole network is more challenging still. Even after recognizing an hourglass, understanding the modularized functions at the neck may require insider-knowledge. But all of this can be done well in advance of an extreme event and, given several known strategic vulnerabilities, *should* be done in many places. Where this is done it is much more likely that feedback (or absence of feedback) will be understood and prompt actions to preserve flows.

Further Reading

A research bibliography of resources referenced above is available starting on page xxx.

The following books and studies provide more information on each of the five problems.

Learning from Megadisasters: Lessons from the Great East Japan Earthquake. Edited by Federica Ranghieri and Mikio Ishiwatari

The Run on Daily Foods and Goods after the 2011 Tohoku Earthquake by M. Horia and K. Iwamoto

Hurricane Sandy Event Analysis Report by the North American Electric Reliability Corporation (NERC)

Overview of Response to Hurricane Sandy-Nor'easter and Recommendations for Improvement U.S. Department of Energy Office of Electricity Delivery and Energy Reliability

Superstorm Sandy After-Action Report by Water/Wastewater Agency Response Network (WARN)

Strengthening Post-Hurricane Supply Chain Resilience: Observations from Hurricanes Harvey, Irma and Maria by the National Academies of Science, Engineering, and Medicine

Out of the Whirlwind: Demand and Supply After Hurricane Maria by Philip J. Palin

The New (Ab)normal: Reshaping Business and Supply Chain Strategy Beyond Covid-19 by Yossi Sheffi

The Preliminary Supply Chain Lessons of the COVID-19 Disruption by Kim Sundtoft Hald and Paula Coslugeanu

A Case Study in Supply Chain Resilience—Private-Public Collaboration to Facilitate Flows: The Experience of Puget Sound early in the Pandemic by Philip J. Palin

How to Avoid Gas Shortages in the European Union in 2023 by the International Energy Agency

The European Union's LNG Supply Security by Frank Umbach (GIS)

PRINCIPLES

A rule or basic idea used to choose among potential solutions to a problem or applied to executing a process. Derived from Latin *prīncipium* (beginning, foundation) and closely related to *prīnceps* (first) and *prīmus* ("first") +-*ceps* ("catcher"). What follows are principles of good practice for exploiting systemic supply chain preferences to solve or mitigate problems such as those outlined above.

In my experience problems – and especially failures – are better teachers than success. The more surprise, the more I am motivated to understand what I do not understand and why I failed to anticipate what would happen. Success can be as complicated as any failure. But when I succeed, I am seldom as rigorous in examining how and why.

All five of the prior micro case studies present big problems that produced plenty of failures, personal and otherwise. Each of the cases highlight empirical – observational, experiential, trial-and-error – engagement with problems. Based on these and many more examples, failure is more likely when a problem is complex, observations are superficial, and the conceived solutions being applied do not fit the problem. Treating the Triple Disaster as a perimeter control problem was a source of failure. Deciding that post-Sandy there was a lack of fuel rather than a lack of distribution capacity seriously delayed more productive interventions. Incorrectly assuming there was a food shortage in Puerto Rico distracted attention from solving other very real problems.

Our direct observations are informed – or sometimes subverted – by our problem-solving preferences. Given our prior experience we arrive at every new problem with a preexisting orientation. Prior experience gives each of us a preferred problem-solving toolkit. If new problems are authentically, systemically similar to prior problems, our chances of problem-solving are multiplied. If, however, we want to use a hammer when a scalpel is better suited (or vice-versa), we will add to our problems.

For most of us, catastrophes are uncommon. Our existing toolkits are not well-stocked for this purpose. The systemic sources of catastrophe can also be obscure. It is not unreasonable to guess that lack of retail fuel implies lack of regional fuel supplies. But this is a naïve diagnosis. Effective problem-solving in a catastrophic context requires well-informed diagnosis of interdependent systems – especially for supply chains, especially in a potential catastrophe. Accurately assessing how current problems are consistent *or not* with prior problems is fundamental.

My diagnostic tool kit for Supply Chain Resilience depends on, first, the preexisting preferences of high volume, high velocity flows and, second, the methods of network science to discern specific preferences in close to real-time. Because complex adaptive flow networks have preferential attachments, it is possible to find and observe how current flow behaviors are consistent with or deviate from these preferences. When and where there is deviance, the network's preexisting preferences can also provide a framework for finding the most consequential causes and fixing/mitigating the deviance – or recognizing sooner instead of later the implications of being unable to fix or meaningfully mitigate.

Sources for several preferences were summarized in this book's first section. In this third section we look at these preferences (and some related factors) for potential interventions that exploit these innate network characteristics to achieve Supply Chain Resilience purposes.

Each problem benefits from a differentiated diagnosis. If the diagnosis confirms problems emerging from specific preferences or sets of preferences, an intervention strategy is implied and can be tested. Rapid testing, assessment, follow-on diagnosis, and further adaptation is crucial and ongoing. In dealing with a complex adaptive system, like high volume, high velocity supply chains, being able to facilitate the self-organizing, self-healing characteristics of the system itself can be very helpful.

I hope most readers – even if you still disagree – will at least play with the notion that high volume, high velocity demand and supply networks are complex adaptive systems. These contemporary supply chains have been created over the last half-century due to necessity and the pursuit of comparative advantage. In case of catastrophe, supply chain continuity or restoration (or sometimes redirection) is now required if the fundamental needs of large populations are to be fulfilled.

There are numerous opportunities to advance Supply Chain Resilience. The preferences and problems I have experienced suggest there are seven core characteristics of contemporary supply chains that enable seven key principles of Supply Chain Resilience strategy, operations, and tactics. When supply chains are challenged and cascading toward catastrophe, constant and careful attention to these core characteristics will empower calibrated, creative, coherent problem-solving. My foundational seven are:

1. Flow has volume.
2. Volumes have velocity.
3. Velocity is shaped by constraints.
4. Constraints tend toward concentration.
5. Flow networks are common-pool-resources.
6. Flow is predisposed to flow.
7. Probability is not certainty.

Definitions

Flow—Motion in space, Newtonian Force, contiguous movement of objects or value, movement across time, momentum, flux, multiple objects changing position per unit of time, output of demand pull and supply push across space per unit of time. Closely related to percolation. Many batches of refined product are simultaneously carried by the Colonial Pipeline flowing northeast from Texas.

Volume—Mass and/or magnitude, measurement of space occupied or capacity operationalized, quantity, content, loosely linked monads rolling together across space and time, convolution of inputs or outputs, measured units of content turning together per static space and/or time. The three stem Colonial Pipeline consists of two 40-inch and one 36-inch pipe. On most days the 5500-mile-long pipeline contains 3 million barrels of various refined products. (Is this just a very long link or one very oblong node or a vine-like giant component?)

Velocity—Speed plus acceleration, deceleration, and rate of change, in a specific direction or directions. The content of the Colonial Pipeline flows roughly 3-to-5 miles per hour, requiring a rough average of nineteen days to move product from Houston to New York Harbor. More than 100 million gallons of refined product are discharged at almost 400 terminals along the route.

Constraints—To draw tightly as with a rope, to press, to contract, to limit and direct movement, to create tension, to twist, to squeeze, to squeeze flow and/or/therefore velocity, friction, volume limiting, rate limiting, purposeful sizing and sequencing of volume and velocity to optimize flows to fulfill demand at lower temporal or financial costs. Key component of percolation and, often, of punctuation. *This* fuel rack is limited to long-term storage customers who independently contract for maritime resupply and distribution. There are six discharge bays capable of simultaneous filling of tanker trucks owned/contracted by storage customers. Depending on size of tanker and operator efficiency, up to 10,000 gallons can be dispensed in 20 to 25 minutes at each bay.

Concentration—Consolidate, aggregate, to gather into one place, body, mass, or force. To center as in "center of gravity." The Concentration of Force that equals Mass multiplied by Acceleration. Integration and calibration of modules, protocols, functions, and related flows to increase velocity and volumes (especially at the neck of an hourglass, "Constraints that Deconstrain", see more below). *This* grocery distribution center is the destination for about 100 trucks per day that deliver single or closely related products from widely dispersed – sometimes distant – "push nodes". This DC is also the departure point for about 80 trucks per day that deliver a diverse, changing collection of products to several "pull nodes" serving hundreds of thousands of people.

Network—A structure of links (channels, routes, edges, arcs) and nodes (intersections, vertices) that are interconnected, usually interdependent, and percolate, facilitating interaction among mostly independent agents. The US food system is "an interdependent network of stakeholders (companies, financial institutions, public and private organizations), localized in a given geographical area (region, state, multinational region), participating directly or indirectly in the creation of a flow of goods and services geared towards satisfying the food needs of one or more groups of consumers."

Common-Pool Resources—Shared source of capacity, a core resource required by many private parties but by-in-large not owned by private or public entities, and The Commons (as in "Tragedy of..."). A socio-ecological system featuring patterns of human behavior that can be engaged to avoid Tragedy of the Commons. Resources available to be consumed by all and to which access can be limited only at high costs. The US freight *market* often behaves as a common-pool resource.

Continuity: Unceasing, feasible flow, Heraclitan flux, network resiliency, and self-healing stream. Newton's First Law of

Motion (translated): Every body continues in its state of rest, or as continuous motion in a straight line, unless compelled to change that state by forces impressed upon it. “The stream of life is maintained only in continuous flow of matter through all groups of organisms.” (Ludwig von Bertalanffy, Austrian biologist and a founder of General Systems Theory).

Probability—Likelihood. Odds in favor and against. Judgement emerging from probing, testing, and recurring outcomes. The perception of validity, predictability, and a continuing existent. “Belief is having a present impression, for instance of *p* moving, and associating with it an idea of *q*’s moving, so that, before one sees *q* moving, one believes it will move.” Pragmatic alternative to certainty.

Propositions

I have left out many potential principles implied by the Preferences and Problems set out in the first two sections. Possibilities are extensive. My mind and time are limited. I suspect yours are too. These seven have almost always been helpful. On rare occasions when a problem is not susceptible to some combination of these tools, recognizing the miscalibration will often suggest creative adaptations.

These are strategic principles that have operational and tactical implications. These are strategic principles that when effectively cultivated and deployed are likely to enhance readiness and advantage in case of catastrophe. By investing in these strategic principles *before*, less will be lost after. Supply Chain Resilience options to reclaim what has been lost will likely be better.

Below are propositions for translating these seven principles into potential strategic advantage. Strategic priorities are then operationalized and some tactical examples are outlined. Strategy aims to set preconditions for success. The less strategic investment (or wrong strategic investment) the more unlikely is success.

Proposition 1: Know what volumes are most important to you and why. Water? Food? Fuel? Pharmaceuticals? What else (and why)? Given your risk vectors, anticipated consequences, and population needs, what volumes are most necessary and/or most at risk?

Proposition 2: For volumes chosen, identify origins and channels for these volumes. If velocity is seriously disrupted locally or between your locality and the points of origin, what will be the impact on volumes? Given preexisting inventories and surviving velocity, how long do you have to restart flow?

Proposition 3: Given the scope/scale of your volumes and velocity, what are the constraints that matter most (especially constraints that deconstrain)? Grid power? Roads/bridges? Number of trucks/truckers? Fuel for trucks and backup power? Transaction processing? What?

Proposition 4: Know where your volumes, velocity, and constraints are concentrated. Where are your water sources, grocery distribution centers, fuel racks, high volume channels, and other "London Bridge" or "Suez Canal" or "hourglass necks"? Which of these are most at risk? What are the proportional contributions of each of these concentrations? Are there reasonably conceivable alternatives for any of these concentrations?

Proposition 5: Given the volumes, velocity, constraints, and concentrations you have now identified, characterize how this network currently operates. What and where are the biggest flows? Where and how does this network flow? What are the network's preexisting strengths? What are the preexisting vulnerabilities? Given your strategic assessment, what operational priorities are suggested?

The outcome of these first five Propositions provide a solid sense of strategic context. These are the principal resources available just before the crisis. These are the principal vulnerabilities you have inherited. This is the network that will flex (or not), surge (or not), survive (or not) in reaction to the catastrophe. These Propositions are place and/or enterprise specific. Risk depends on specific threats multiplied by specific consequences. Your risk depends on your context. But there are three risk-management propositions that, so far, I have found to be universal:

Proposition 6: Demand and supply networks are common-pool resources. This provides guidance on how to practically enhance resilience. In 2009 Elinor Ostrom was awarded the Nobel Prize for economics largely because of her pioneering work in this field. Dr. Ostrom and her colleagues have demonstrated what works – and as important, tempting choices that increase the chance of failure. More below.

Proposition 7: Networks are stubborn. Once flows start they prefer to persist. When they stop, it can be very difficult to restart flow. So, the best strategy is to do whatever is possible to facilitate continuity: remove impediments, repair damages, effectively express pull to size and target push.

Proposition 8: Life is uncertain, especially in a crisis. Don't wait for certainty. Consistent with the network propensities unveiled by the first five propositions, choose actions more likely to restore the highest proportion flows available, improve velocities, and move volumes as close to pull as possible. Carefully observe how the network responds, reinforce or revise as this behavior signals. What does the response say about which preexisting preferences are most and least troubled? What constraints – and where –seem to be generating the most flow friction? Treat uncertainty as a teacher who will quickly expose bad choices but will also celebrate and work to build on good choices. Which principles are most relevant in your particular context? Diagnosis, exploration, and testing – in a word: problem-seeking – precedes effective problem-solving.

Interventions

In my experience almost everyone – myself included – discounts worst case possibilities. Even direct experiences of serious harm are typically less motivating after a year or two or three. This is *not* the most perverse human pattern; it can be a constructive characteristic of psycho-social recovery.

But this means that catastrophe preparedness – and therefore Supply Chain Resilience – requires an unusually disciplined angle and pace of engagement. Supply Chain Resilience especially requires *strategic* engagement.

Doing something practical with the Principles and Propositions outlined above requires pre-crisis preparedness. Knowing the most important flows, volumes, velocities, constraints, and especially the most concentrated constraints involves homework and testing. The process can begin with personal impressions, some good guesses, and googling. But valid strategic insight requires working with the people who shape and speed the most important flows.

The public sector – federal, state, local – usually gives much more attention to catastrophic possibilities than the private sector. But there is a recurring tendency for the public sector to frame the catastrophic in terms of *recent* "worst cases" (which are often far from the worst). For example, while Japan has experienced historical examples of even worse earthquakes and tsunamis than the 2011 Tohoku Triple-

Disaster, much of Japan's shoreline preparedness had been benchmarked and organized around the consequences of the 1960 Valdivia (Chile) tsunami – that was far less than the maximum height (20 feet) of the 2011 event (130 feet) and did not combine with a local seismic event. Preparing for the 1960 worst case only modestly contributed to mitigating the 2011 much-worse case.

The public sector also prefers to respond with resources they own and can control, rather than facilitating independent sources of flow. In the 2011 Triple Disaster Japan spent almost ten days actively excluding commercial operators from the disaster zone, each day falling farther and farther behind in delivering volumes at velocities survivors required. Japan's emergency response agencies learned from this mistake. In the 2024 Noto Peninsula New Year's Day earthquake commercial flows began within 48 hours. But the policy-strategy-practice preconditions for such private-public collaboration are anemic in most places – and still a bit awkward even in Japan.

Meanwhile the private sector tends to overestimate public sector capacity for catastrophe response. For example, there are roughly 1.4 million active-duty US military personnel. On most days most of these personnel are fed by flows from commercial supply chains. There are also significant stashes of Meals-Ready-to-Eat and related products to support sudden military deployments (and domestic/international humanitarian efforts). MREs are produced by a handful of private sector firms under contract with the Defense Logistics Agency. The DLA purchases over 95 percent of all MREs produced in the United States. The annual flow is roughly 2.5 to 3 million cases per year. There are usually a dozen meals in each case. This is the scope/scale of pull around which MRE push capacity is constructed. MRE push capacity can be expanded, but this takes time and money. So, the preexisting public sector (really, private sector too) capacity to deliver MREs tops-out at about 36 million meals, roughly equal to the weekly flow of one market-leading grocery distribution center serving a major metro area. If the number of hungry survivors is, say, 100,000 this could provide minimum sustenance for about six months (if there is not a major military deployment or another disaster). But with 1 million survivors, we are down to less than three weeks push capacity. In early March 2024 the US government air dropped MREs into Gaza to help 2.3 million hungry people. The first set of pallets parachuted over the beach totaled 38,000 meals.

The previous paragraph is a quick example of using Propositions 1, 2, and 3 to assess strategic reality. My take-away: In large-scale, extended-scope catastrophes, the public sector does not have the capacity to replace lost food flows. Only preexisting—mostly private sector—flows have sufficient capacity to feed catastrophe-scale numbers of survivors for any extended period. Public sector capacity is crucial where private sector flows cannot go. But the only way to fulfill catastrophe-scale pull is with pre-catastrophe push capacity.

Strategic thinking depends on purposes, goals, and context. Are there 100,000 survivors or 1 million or 3 million? Will the grid be gone for three days or three months? Is your impact zone 5000 square miles, 10,000 square miles, or 50.000 square miles?

5000 SQM

10,000 SQM

50,000 SQM

If time, space, and population factors are on the lower end, the best Supply Chain Resilience strategy is probably to actively communicate current and changing conditions to supply chain players and (mostly) stay out of their way. Where pull persists, they are predisposed to push through. But if time, space, and population disruptions are on the high end—and need cannot signal pull – both private and public sectors will need to find creative and courageous adaptations to novel conditions.

Strategic Choice

In my experience, strategy is given a great deal of lip service and not much serious, sustained, self-critical thought or consistent effort. Strategic problems are explained away. Strategic opportunities are ignored.

Strategy is how we try to claim comparative advantage when dealing with problems, change, and uncertainty. We prefer continuity and certainty. We will often bend our observations to fit these preferences. If our current condition is consistent with prior conditions, then inherited strategic choices will probably serve us well-enough. Persistence can be a virtue. But when our context has fundamentally changed, this same persistence will accelerate failure. In its Greek original the word for catastrophe suggests a sudden turn. We have departed our prior path. We may be unable to return to that path. What should we do now? Strategic thinking and doing determine how we answer this very open question.

There is no evidence that Sun-Tzu wrote or said it, but he is often given credit for, "Strategy without tactics is the slowest path to victory. Tactics without strategy is the noise before defeat." Meaningful strategy gives myriad tactics a shared direction when our prior path has disappeared. A well-conceived, actively communicated, and widely understood strategy will calibrate thousands of individual choices in real time, even amid cacophonous uncertainty, even when command-and-control is replaced by silence.

Many suggest that strategy identifies the destination while tactics are the specific steps taken (and operations decides modalities and schedule) in whatever direction. This is true-enough but obscures the turmoil, turbulence, and risk that exist between our current location and our strategic target, especially as we try to move through a chaotic landscape toward a new and unfamiliar destination. Given the flood of demand and/or drought of supply, how can I cross from here to there? The most beneficial strategies don't just choose where to go but discern *the* direction most likely to move through the turmoil, mitigate our risks along the way, and deliver comparative advantage when we get there.

By going this way (instead of that way) we can achieve our purposes more quickly with the fewest losses. Moving toward this new destination – instead of trying to defend a now untenable position – can give us the most options for pursuing our purposes in the face of the unexpected. Purpose drives strategy. Being clear about purpose is fundamental.

In a disaster is my purpose to move the most MREs I can or to feed the most people possible? These are not contradictory goals. These can be complementary objectives. Feeding is the purpose. Moving MREs is one means of achieving the purpose. Purpose is usually multimodal, especially in a crisis, even more so in a catastrophe.

When you don't – and won't – have enough MREs to feed survivors, the risk context requires choosing a more ambitious goal. The unfamiliar – novel – challenges of feeding several hundred thousand survivors with resources owned and moved mostly by independent others encourages strategic thinking to unlock unusual constraints and embrace unfamiliar opportunities. The best strategy will convert vulnerabilities into opportunities.

Private-Public Strategies

For purposes of Supply Chain Resilience – to serve survivors of a catastrophe – an effective strategy of private-private and private-public operational relationships will almost always deliver significant comparative advantage in worst cases.

In just about every geography, market-leading competitors for food, fuel, pharmaceuticals, and most other freight flows depend on the same infrastructure: power grid, road networks, fuel pipelines, fuel racks, truck stops, telecommunications, financial services, etc. Most receive flow from the same set of upstream sources, traveling very similar mid-stream routes. Serious external problems for one commercial operator are usually experienced to lesser or greater degrees by all major operators that share geographic proximity. Solving or mitigating these external sources of friction for one operator will often facilitate flows across the entire network. In a serious and sustained crisis, the failure of any market leading provider – upstream, midstream, or downstream – will seriously stress all surviving providers.

Continued commercial flows are fundamental to achieving public sector purposes in a catastrophe. The more quickly and fully flows restart and reconnect with demand, the better for every survivor. The more private sector capacity persists and can be pushed, the more public sector capacity can focus on serving those left outside private sector flows.

These fundamental realities reinforce how contemporary supply chains often fit the definition of Common-Pool-Resources developed by Elinor Ostrom and others. This is an empirically deep and fertile field of research, analysis and action. Many findings are situation specific. But in her 2009 Nobel Prize address Dr. Ostrom outlined six core attributes of effective private-private and private public relationships.

Below Dr. Ostrom's six attributes of successful collaboration are in bold italics. I then outline how I have experienced these attributes in the context of Supply Chain Resilience. Dr. Ostrom's claims have been extensively researched, tested, and confirmed. My claims are earnestly offered but would benefit from more rigorous replication and testing.

Communication is feasible with the full set of participants. When face-to-face communication is possible, participants use facial expressions, physical actions, and the way that words are expressed to judge the trustworthiness of the others involved.

One-on-one face-to-face communications is usually the way to start (for the reasons noted by Dr. Ostrom). Someone needs to take the risk and make the effort to be a broker, matchmaker, ambassador… When three or five or seven private and public Supply Chain Resilience participants are ready to talk face-to-face, host a lunch or find an interesting neutral location or just share coffee at some mutually convenient venue. Organize the conversation around a handful – no more than five – authentic and almost unanswerable questions. Keep the discussion well under two hours and more informal than not. Investing time and effort to allow participants to "judge the trustworthiness of the others involved" will pay off.

Reputations of participants are known. Knowing the past history of other participants, who may not be personally known prior to inter action, increases the likelihood of cooperation.

Reputations often involve preexisting – and troublesome – stereotypes of public sector "bureaucrats", private sector "pirates", mercenary competitors, "pointy headed academics", time wasting do-gooders, and plenty more. Getting beyond these stereotypes with a core private-private group and eventually a bit larger private-public group is foundational. This can usually be advanced by bilateral discussions or quick teleconferences or Zooms. But face-to-face continues to be the best and most long-lasting investment.

High marginal per capita return (MPCR). When MPCR is high, each participant can know that their own contributions make a bigger difference than with low MPCR and that others are more likely to recognize this relationship.

Involving smaller numbers of the most network-influential participants is almost always better than larger groups. For example, in most US metro areas three-quarters of groceries are sold by five or fewer market leaders. Those five meeting together improve prospects for high MPCR.

Entry or exit capabilities. If participants can exit a situation at low cost, this gives them an opportunity not to be a sucker and others can recognize that cooperators may leave (and enter other situations) if their cooperation is not reciprocated.

Research by Ostrom, Kahneman, Allport, and many others find that humans expend enormous effort to avoid being a "sucker". Most of us, most of the time, are more motivated to *avoid* being a sucker than to advance our self-interest… even less the common interest. Informal structures and processes defuse sucker-avoiding behaviors. Formal structures and processes often inflame sucker-avoiding behavior, especially if proposed – or imposed before trust is shared among a core group.

Longer time horizon. Participants can anticipate that more could be earned through cooperation over a long time period versus a short time.

Relationships can be advanced by time-specific projects but should not be confused with – or subverted by – project-specific timelines. Modest time investments per encounter extended over many long-term encounters are much more sustainable that intense time investment in the near-term.

Agreed-upon sanctioning capabilities. While external sanctions or imposed sanctioning systems may reduce cooperation, when participants themselves agree to a sanctioning system they frequently do not need to use sanctions at a high volume and net benefits can be improved substantially.

So far, the sanctions that I have personally seen emerge from Supply Chain Resilience collaboration have been informal and affirmative. A combination of positive preexisting relationships and very real mutual needs facilitate constructive behavior over the course of crisis response. Participants enter collaborations at will and exit sanction-free.

I am aware of public sector efforts – and existing authorities -- to formalize negative sanctions. In my experience these efforts tend to distract from collaborative possibilities and can even motivate non-collaborative self-seeking behavior. I can imagine the emergence of the sort of self-sanctioning system that would amplify collaboration. But I do not see this as likely anytime soon.

Common-Pool-Resources feature many more situation-specific attributes, many of which are relevant to Supply Chain Resilience. But *consistent* engagement of just these six would be a very good start.

Elinor Ostrom concluded her Nobel address with:

> Designing institutions to force (or nudge) entirely self-interested individuals to achieve better outcomes has been the major goal posited by policy analysts for governments to accomplish for much of the past half century. Extensive empirical research leads me to argue that instead, a core goal of public policy should be to facilitate the development of institutions that bring out the best in humans. We need to ask how diverse polycentric institutions help or hinder the innovativeness, learning, adapting, trustworthiness, levels of cooperation of participants, and the achievement of more effective, equitable, and sustainable outcomes at multiple scales.

In my judgment this articulates the most important challenge facing Supply Chain Resilience. If we can foster thinking, behavior, and institutional capacity consistent with this vision, our practical ability to serve survivors of catastrophe will be multiplied.

Principled Strategic Deployment

Seven core characteristics of high volume, high velocity supply chains have been identified. These are perceived as principles of persistent network behavior. Eight propositions have been set out for exploring and exploiting these principles for Supply Chain Resilience purposes.

A potential strategy for private-private and private-public operational relationships has been outlined. Six empirically demonstrated attributes of effective private-private and private-public relationships have been referenced.

Now, how can we engage these attributes to execute this strategy to leverage these principles to achieve effective, equitable, and sustainable *flow* outcomes at multiple scales? Below is a possible framework.

Principle: Flow has volume.

Strategic Priorities: Pre-select a minimum set (say, seven) of flows and volumes most important to the survivors of the relevant catastrophe context(s).

Operational Requirements: Ongoing research, assessment, and outreach to clarify survivor needs given catastrophic risks, current sources of flow volumes, and size/scope post-catastrophe volume changes and options.

Tactical Examples: Water, food, fuel, pharmaceuticals, medical goods, freight (general, cold-chain, alternative modes, etc.), and shelter components (roof tarps, tents, expeditionary housing, etc.) are seven recurring classics. But tactical priorities should reflect local risk contexts, however "local" is defined.

Principle: Volumes have velocity.

Strategic Priorities: Find places and players that make and move the priority volumes identified.

Operational Requirements: Identify and confirm facilities, channels, and modes used to move volumes and where these volumes are usually discharged.

Tactical Examples: Delivery routes between Distribution Centers or fuel racks or other midstream facilities and downstream retail venues. Origins to targets for flows serving food banks and neighborhood pantries. Public water networks.

Principle: Velocity is shaped by constraints.

Strategic Priorities: Focusing on the volumes chosen as most important, identify constraints (especially at the neck of the hourglass) that have outsize influence on speed and/or direction of flows.

Operational Requirements: Ongoing research, assessment, and outreach to measure velocity and identify principal functional and systemic factors that generate velocity.

Tactical Examples: Trucks and truckers available, fuel for trucks, pallets, operable forklifts, real-time transaction signals, electricity and telecoms to generate transaction signals.

Principle: Constraints tend toward concentration.

Strategic Priorities: Find places and people where volumes and/or velocity are disproportionally concentrated. Are these concentrations geographically dispersed or proximate? Who owns/operates these concentrations?

Operational Requirements: Ongoing research, assessment, and outreach to identify market-leading sources of flow and their upstream, midstream, and downstream facilities.

Tactical Examples: Water networks, transportation systems, grocery distribution centers, and fuel pipelines-terminals-racks that reflect a disproportionate share of flow.

Principle: Flow networks are common-pool-resources.

Strategic Priorities: Map and validate the pull-push ecosystem for high priority volumes.

Operational Requirements: Workshops and tabletop exercises with the owners-operators of concentrated flow to validate maps, engage in collaborative problem-seeking, and conceive creative approaches to Supply Chain Resilience.

Tactical Examples: Small private-private, larger private-public, and annual community-wide tabletops that are conceived as stress-tests for flow and private-private and/or private-public collaboration. These events are organized around core strategies, Concepts of Operations, and problem-seeking *not* around detailed tactical plans.

Principle: Flow is predisposed to flow.

Strategic Priorities: Find where preexisting flow has survived, reinforce, amplify, and redirect as needed by survivors. Find constraints that can be de-constrained to release impeded flow. Avoid introducing additional friction. Do no harm.

Operational Requirements: Preexisting relationships with people and places that have significant preexisting volumes. Communication capabilities and protocols for signaling post-event status and needs. Familiarity with a variety of flow facilitation injects and techniques.

Tactical Examples: Debris clearance, weight waivers, public safety escorts, delivery curfews lifted, truck staging areas opened, cross-docks deployed, focused traffic management provided, more flexible hours-of-service regulations, expedited public health inspections.

Principle: Probability is not certainty.

Strategic Priorities: Front-line and rear-echelon decision-makers expect to be surprised and experience failure. Decision-makers proactively probe plausible strategic openings and tactical opportunities. Rapid exploitation of evidence that flow can be restarted and sustained.

Operational Requirements: Involve both leaders and operational personnel in private-private and private-public problem-seeking workshops and tabletops exercises. Invest in mitigation and response capabilities. Cultivate risk-tolerant – even risk-embracing – decision making.

Tactical Examples: Include high-stakes failure in problem-seeking workshops and tabletop exercises. Think-through and work-through how to preserve collaborative capacity and decision-making confidence in high-stress unpredictable contexts.

These seven angles of engagement provide an approach to Supply Chain Resilience that reflects core characteristics of the demand and supply network. By working with the network's principal preferences, flow potential and recovery are enhanced, and unnecessary new friction is more likely to be avoided.

Putting Principles into Practice

Over the years I have organized several Supply Chain Resilience efforts and participated in even more. Dr. Ostrom's core attributes have been prominent in both the success and failure of these activities.

The most common cause of failure has been where and when both the private and public sectors are persistently skeptical regarding catastrophic risk. If Supply Chain Resilience is viewed as a near-term cost with little or no likelihood of delivering a benefit, it is tough to get a conversation going – much less a principled strategic process.

But even with undeniable risk readily acknowledged a good proportion of Supply Chain Resilience efforts fail because key participants (usually public sector participants) insist on treating the complex adaptive system of demand and supply like some sort of engineered machine rather than an evolving ecological system. Engineered machines are expected to predictably respond to well-established command and control protocols. That is not how high volume, high velocity supply chains behave on their very best days, much less during a catastrophic cascade.

Another cause of failure (that I consider closely related to wanting to work with an engineered machine) is tumbling into an Alice-in-Wonderland rabbit hole of deeper and deeper research – to the exclusion of outreach and relationship-building. Human relationships are so complicated (you may have noticed). Surely if we just keep looking, we will find the off/on and slow/fast switches. Contemporary high volume, high velocity supply chains are sometimes described as "socio-technical systems." The social dynamics are persistent, powerful, and not possible to preempt.

Despite these frequently pernicious preferences, I have also been privileged to see serious, substantive collaboration emerge between erstwhile competitors and across the private-public chasm. The consistent characteristics of these success stories have been 1) a shared sense of significant risk, 2) a strong sense of potential mutual benefit, and 3) an enthusiasm to meaningfully engage a *very interesting* problem. One supply chain executive exuded, "This is three-dimensional chess. There are almost no right/wrong answers. Instead, there are better/worse questions."

When the right people ask good questions – in a context consistent with Elinor Ostrom's six attributes – strategic possibilities and tactical options proliferate.

A Fable of Supply Chain Resilience

This is a true story about a real place and an actual private-public process—as Aesop might render it.

Once upon a time in a beautiful place sitting across several significant seismic faults people asked, "What should we do – what can we do – when the earth shakes very hard."

"And shakes again and again," one of them added.

So, one of the men went to the grocers to ask about food and one of the women asked the mayor about water. Others traveled to talk to those who make fuel and deliver electric power. After the man talked to five different grocers, he talked to builders of roads and bridges, then had conversations with several truckers. After her talk with the mayor the woman talked with physicians and nurses.

Everyone agreed the earth would one day shake very hard. No one felt ready for that day. A few disliked the conversations, but most were glad to work through their worry with a new friend.

Each conversation was unique. But three common truths emerged from the differences:

- Connections will break for water pipes, electrical lines, roads and bridges, fuel pipelines, and much more.
- When connections break, distance will be difficult to overcome. Most water, food, fuel, and medicines for this beautiful place come from someplace else, sometimes from very far away over the mountains.
- Rapid repair of connections will be attempted but cannot be guaranteed if the shaking is very bad.

"Especially if it shakes again and again," the same one added again.

After these discreet conversations an invitation was extended for the mayor, grocers, truckers, and all the others to continue their conversations in a loft above the local coffee grindery. Most came. Short versions of each story were repeated. The common challenges were confirmed. The mayor reported how the kingdom will try to do to help the beautiful place when some day the earth will shake very hard.

It was not an encouraging conversation.

But by confronting their common problems in the same room at the same time, a shared sense of vulnerability *and possibility* emerged. Each person's daily tasks were revealed as individual strings pulling or pushing abundance toward need. When the earth's shaking does someday slash, every surviving string will be a cherished lifeline.

In that fragrant grindery it was soberly decided that the worse the shaking, the more important it is for everyone in the room to do what they can to help each other. To be ready to do this, they needed to understand each other better. So, they met again. The grocers talked to each other and then with the truckers who delivered to them. Each string sought to know every string with which it was woven. Along the way much was learned and new friends were made.

Most decided they were not smart enough to specifically plan for what would be needed; but it would be essential to know more about the connections on which they each depend so they could make smart, creative decisions once the shaking was done.

"Or between shakes", a different-than-usual someone added.

These small-group conversations were barely begun when the beautiful place was surprised by plague. The earth did not shake, but for months many neighbors, friends, and family were ill and some died. A long-time grocer was the first to die.

In some other places where plague raged, mayors tried to separate from the outside world. But in the beautiful place it was understood that far flows are needed. In the beautiful place food remained abundant, fuel continued to flow. The grocers talked to truckers. The truckers talked to the mayor. The mayor talked to the king. Seams continued to be sewn. Human connections preserved physical connections. It was a troubled, tumultuous time, but flow persisted.

We cannot know how hard the earth will shake, but we can choose to be ready with knowledge, meaningful relationships, creativity, courage, and care for one another.

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I could have, perhaps should have, rendered this same true story as a network scientist might. There are plenty of opportunities to consider how percolation, concentration, punctuation, and related preferences and patterns were very much at play in this beautiful place.

As the pandemic proceeded officers of the "king" (various kings really) not involved in the original seismic-related conversations became increasingly prominent, officious, and counter-productive. A constructive process demonstrated its effectiveness in a very real slow-onset disaster, but I don't perceive most of the private-public relationships survived the pandemic. On the other hand, many of the private-private relationships continue to resonate. Will the full range of these relationships resurface when the earth shakes very hard?

I don't think this mixed result subverts what the fable can tell us and may even reinforce the moral of the story. The process featured a shared sense of risk, interdependence, and potential mutual benefit. The core participants consisted of a small group of market leaders who already knew – or soon knew – the reputations of each other, who could easily enter and exit informal discussions, communicating primarily face-to-face to better understand the nature of their shared problems and develop a strategic approach to achieving their individual and common purposes.

These too are preferences. But these are preferences that have been tested, measured, and – so far – confirmed across a wide range of use-cases. As such, these behavior patterns are promising leading indicators for innate, even systemic preferences – not just personal preferences. These are potentially powerful strategic principles to inform what we choose to do and not do in preparing for and responding to catastrophe. Testing and adapting these principles can connect push and pull on the worst day.

Further Reading

A research bibliography of resources referenced above is available starting on page xxx.

Clausewitz on Strategy by Tiha von Ghyczy et alia

Beyond Markets and States: Polycentric Governance of Complex Economic Systems by Elinor Ostrom

Rules, Games, & Common-Pool Resources by Elinor Ostrom et alia

Competitive Strategy by Michael E. Porter

Competitive Advantage by Michael E. Porter

Mission Improbable by Lee Clarke

Predictable Suprises by Max H. Bazerman and Michael D. Watkins

Catastrophe by Richard A. Posner

A Case Study in Supply Chain Resilience—Private-Public Collaboration to Facilitate Flows: The Experience of Puget Sound early in the Pandemic by Philip J. Palin

Red Sea Redux

This will be a three-to-five-page revisiting of Suez Canal flows since the Houthi attacks began… comparisons to the Ever Given story and leaning into an appropriate moral of the bigger story.

Research Bibliography and References

Index of Key Concepts

ABOUT THE AUTHOR

Philip J. Palin is the son and grandson of grocers, a former college president, and serial entrepreneur who has served as a Supply Chain Resilience subject-matter-expert with the National Academies of Sciences, Engineering, and Medicine, Institute for Public Research at CNA, Department of Homeland Security, FEMA, and with several states and cities. He has researched and engaged in a wide range of extreme events including the 2011 Triple Disaster in Japan, Superstorm Sandy in 2012, Hurricane Haiyan (Yolanda) in 2013, Hurricanes Harvey, Irma, and Maria during 2017, and most named storms during the 2018 -2023 hurricane seasons. In 2020-2021 he was involved in pandemic response and preparedness, especially focused on flows of food and medical goods. He works with federal, state, local and private sector leaders to prepare for and respond to complex wide-area catastrophic events involving dense populations. He is the author of several books and articles, including *Out of the Whirlwind: Supply and Demand After Hurricane Maria* and *He Looks at the Earth: Catastrophe, Recovery, and the Cascadia Earthquake*. He is also the author of an online self-study course in Supply Chain Resilience offered by the Center for Homeland Defense and Security at the Naval Postgraduate School. Other publications by Philip J. Palin can be found at supplychainresilience.org/