A Bat Sneezed and the Economy Collapsed

Launching the Fourth Industrial Revolution in a Pandemic Age

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Idea in Brief

- Mass Production, Lean Production, and bottom-line financial metrics created unprecedented value to society in the 20th century but have now reached their limits and create a global systemic risk. The aerospace industry has been particularly hard-hit.
- The human population has expanded into the former wilderness where viruses thrive in rodents, birds, pigs, and bats. COVID-19 is the sixth pandemic of the 21st century, and we can expect more to follow.
- Societal growth requires new technologies and new management theory, as envisioned in the Fourth Industrial Revolution. Products will become connected and autonomous, and economics will measure impacts on People and the Planet, as well as Prosperity. This is known as the Triple Bottom Line.

Introduction

The <AIAA conference name> kicked off the first week of January 2020 with a variety of face-to-face networking sessions… and by March this seemed unimaginable as the world suffered the effects of the COVID-19 pandemic. At the time of the conference the only known cases were in Wuhan China, but later research finds that unrecognized cases existed in at least the US, France, and Italy as early as December 2019.

This is all by way of saying that two days after speaking at the conference I developed 15 days of COVID-like symptoms, and as was seen over the coming months (and soon… years) we have no means of knowing when a novel virus is being distributed throughout the world. Such diseases dramatically impacts the economics of the commercial airline industry, and the industry has a dramatic ability to impact the economics and health of the world, by distributing disease.

US traveler throughput collapsed in April 2020, 14 months later it was still 700,000 passengers per day below 2019 levels and much of the world is having an even slower recovery than the U.S. (Figure 1). Airlines have lost tens of billions of dollars, expect a return to pre-COVID levels to be years away, and will require the worldwide distribution and adoption of vaccines. Boeing, Airbus, and their suppliers cut tens of thousands of jobs (Conger & Griffith, 2020), and dramatic shifts are taking place in the economics of airline profitability and the manufacturers which serve them.

Figure 1: US Air Travelers
(TSA Passenger Throughput, 2021)

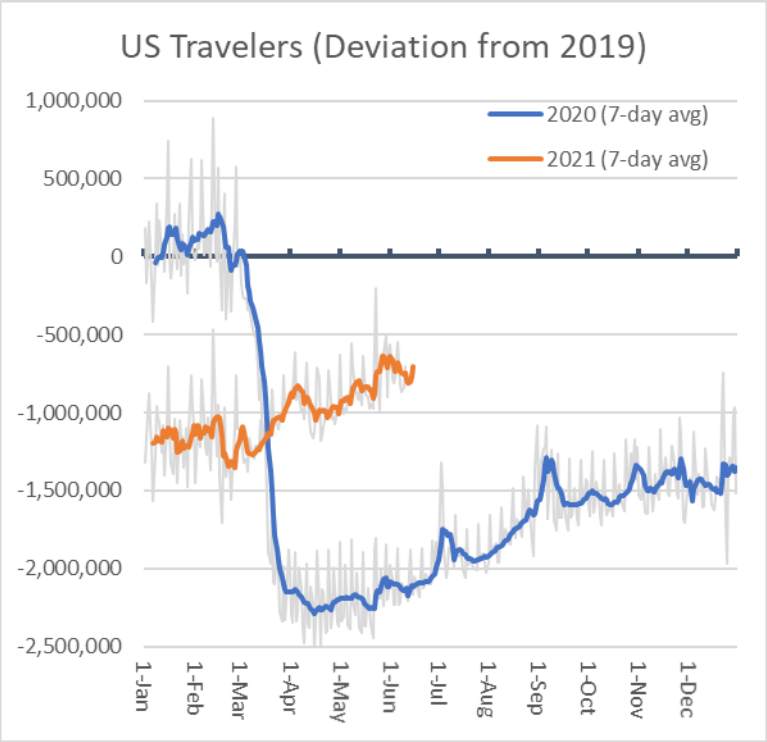


Table 1: World Passenger travel
(Corona Virus Airline Schedule Data, 2021)

	May-21 vs May-19
Global	-42.7%
Australia	-32.8%
Brazil	-54.4%
China	8.7%
France	-70.4%
Germany	-79.2%
India	-44.9%
Japan	-56.9%
Mexico	-17.5%
Singapore	-83.1%
South Africa	-47.6%
South Korea	-44.9%
Spain	-68.2%
UAE	-51.4%
United Kingdom	-85.3%
USA	-27.2%

The industry relies on world-wide public health as travelers consider their entire infection risk, from the time they leave home until they return. It is not enough for aircraft, airlines, and airports to protect passengers: what about the taxis, the hotels, the offices, the restaurants, the stadiums, and the theme parks which travelers attend?

Destination locations face risks as well. Respiratory viruses may spread long before they are recognized. The SARS-CoV-2 virus likely originated in bats, jumped to humans in China, then Europe, New York, throughout the U.S., the world, and even zoo animals (McAloose, 2020). Since the outbreak, nations and states closed their borders and enforce quarantines upon arrival; business trips which formerly took a week now require a month, if the traveler is allowed to enter at all. Businesses are learning to replace air travel with Zoom meetings, and large shifts are occurring in the nature of work (Gratton, 2021).

Is This the Economy That We Want?

From the New York Times on 15-July-2020 (Tankersley & Casselman, 2020):

> "WASHINGTON — The United States economy is headed for a tumultuous autumn, with the threat of closed schools, renewed government lockdowns, empty stadiums and an uncertain amount of federal support for businesses and unemployed workers all clouding hopes for a rapid rebound from recession.

> "… failure to suppress a resurgence of confirmed infections is threatening to choke the recovery and push the country back into a recessionary spiral — one that could inflict long-term damage on workers and businesses large and small…

The Economist, on 1-August ("Air travel's sudden collapse will reshape a trillion-dollar industry.", 2020):

> "Around 35% of the global fleet of around 25,000 aircraft is still parked—less than the 70% at the height of the crisis in April but still terrible. Even if traffic recovers to 80% of last year's levels in 2021, as some optimists expect, plenty of aeroplanes will remain on the ground. Citigroup, a bank, forecasts excess capacity of 4,000 aircraft in 18 months' time."

And the Wall Street Journal on 2-September (Cameron, 2020):

> "The pandemic is set to have an even deeper and longer-lasting impact on airlines' finances than 9/11, several industry executives have said. Carriers have spent months trying to get passengers back onto planes after the pandemic nearly halted travel in the spring, including by developing more-thorough cleaning procedures and toughening rules requiring passengers to wear masks. Nevertheless, travel demand has stalled at around 30% of last year's levels. Executives believe it will take years—and likely a vaccine—for it to fully rebound."

A year later, demand for products recovered in the U.S. but supply chains were disrupted. (Sullivan & Deese, 2021):

> "In mid-2020, a global chip shortage emerged when automakers warned that relatively inexpensive semiconductors were becoming scarce and would potentially disrupt vehicle production. In the second quarter, auto parts suppliers cancelled orders for chips due to a six-week industry shutdown to mitigate the spread of the pandemic at vehicle and part manufacturing facilities. Parts suppliers also sought to limit inventories and costs in anticipation of a predicted fall in vehicle demand during a post-pandemic recession.
>
> Automakers are idling plants (in 2021) and furloughing workers as they are unable to maintain production lines as they wait for parts. This shortage will cost the global automobile industry an estimated $110 billion in 2021 and will lead to the production of nearly four million fewer vehicles than automakers had planned.
>
> At the same time, the rapid shift to a work-from-home economy driven by the pandemic increased demand for electronic devices including video-game systems, computers, laptops, and other electronics and for the digital infrastructure and storage to support the increased on-line activity."

From the Harvard Business Review (Gratton, 2021)

> "By the middle of March (2020) the majority of Fujitsu's 80,000 Japan-based employees were working from home,… and appreciating the advantages of their new flexibility. Only 15% viewed the office as the best place to work, with 30% viewing home as best, and the remaining 55% preferring a hybrid model.

> Hiroki Hiramatsu, global head of HR said "We are not going back… the two hours many people spend commuting is wasted – it could be spent on education, training, or time with family" Shared offices are now located all over Japan, often near urban and suburban train stations".

Similar issues quickly appeared throughout the world-wide commercial real estate market. The Time-Life Building in Manhattan houses 8,000 workers at its peak, but the daily average in July 2020 was only about 500. Investment banks with tens of thousands of workers in the New York City area found that they can operate with a smaller footprint.

If workers no longer commute to their local office, why would they take a business trip to another city? The Zoom online meeting platform grew from 10 million to 300 million daily participants in April 2020, echoed by growth at Microsoft, Google, and Cisco (Tara, 2020). The business market for air travel generated two-thirds of airline earnings prior to the pandemic (Investopedia, 2019), but now internet meeting platforms are poised to generate a long-term disruption to this travel.

Complexity and Systemic Risk

In a parallel chapter, Grieves describes simple, complicated, and complex systems, with the former having "inputs, operations, and outputs are easily discernable"; complicated systems are similar to this, "but have more components which interact, and … may be decomposed into (multiple) simple systems". But Grieves highlights that there is "not good agreement as to what constitutes 'complexity'", and that "complexity drives the need for Digital Twins". I see this as well and provide an example in the section below titled *Digital Manufacturing Twins*.

(Senge, 2006), highlights another aspect of complexity, and notes the systemic nature of reinforcing feedback (where growth encourages growth) and balancing feedback (where growth creates a counteracting force). This is discussed in the section *Systems Thinking and Economic Disruption*.

A century ago, Henry Ford, William Boeing and others developed a systemic reinforcement in human prosperity through the mass production of *complicated* products but did so with little understanding for the *complexity* which one industry places upon another, or upon the planet. We see now how western auto industries and their supply chains followed a reinforcing growth path which eventually included Japan, Asia, and regions in southern China which are home to viral-laden bats. The virus then spilled over to humans, some of whom traveled on planes and spread SARS-CoV-2 throughout the world.

Travel and entertainment industries collapsed, hospitals were overwhelmed awaiting improvements in public health, and a year later the auto industry suffers for the lack of a resilient supply chain. (As does the pharmaceutical industry, discussed in the section *Shifting the Burden…*) In a parallel chapter, Khalid et al., refer to the increasingly complex (pre-pandemic) air traffic control system, but the level of complexity diminishes as travelers first stay home to avoid disease, and choose instead to work from home. The need for air traffic control is being replaced by a Zoom scheduling app. The symptoms and solutions of complexity appear from unexpected directions, and in this case there is no need to solve the air control complexity problem if we don't first solve the problems of worldwide public health. In a broad-scale system of systems, communicable disease and air travel are inextricably linked.

In another parallel chapter, Flumerfelt refers to the very important need to understand "human systems", while this chapter focuses on the natural world as the system which encompasses all the others, and that the poorly understood complexity of nature, culture, and economics limit the growth of

humanity. The thesis is that humans shifted their economic burdens onto the planet, and now the planet is shifting the burden back. The chapter follows three main themes:

- A short history of the Second Industrial Age and systemic growth.
- A description of 'Systems Thinking', using events of the COVID-19 pandemic as examples.
- Predictions for future decades, as technology and economic goals address the necessary 'triple-bottom-line' of Planet and People, and Prosperity.

Industry 2.0: Mass-producing an Efficient Pandemic

Klaus Schwab, head of the World Economic Forum posits that there have been four revolutions in the Industrial Age (Schwab, 2015):

- "The First Revolution used water and steam power to mechanize production,
- The Second used electrical systems to enable mass production,
- The Third saw the introduction of electronics and information technology to automate production,
- The Fourth is blurring the lines between the physical, digital, and biological spheres."

The following is a brief history of the Second Revolution in the automobile industry, from *The Machine That Changed the World* (Womack, Jones, & Roos, 2007) as a prelude to a discussion of the Fourth.

1920 - 1950: Ford, Sloan, and Mass Production

Around 1910, Henry Ford saw inefficiencies in existing automobile manufacture and through mass-production was able to increase worldwide volume by a factor of 1000, to two million vehicles per year. In the late 1920's, Alfred Sloan of General Motors improved economic efficiency by measuring a short list of financial metrics, including earnings, revenue, inventory, and market share. In the coming decades, nearly all industries adopted these approaches.

The automobile was a boon to farming and brought increased food security throughout society; farmers used tractors to grow more crops, and vehicles to ship them to distant markets. During World War Two auto plants manufactured Jeeps and airplanes; following the war the expanding U.S. economy allowed millions of Americans to move off farms and into cities. As availability to food and conveniences became more secure, new technologies emerged and led to growth in many new fields like electronics, entertainment, medicine, and education.

1950-2000: Lean Management

As cities grew, traffic increased to become 'gridlock' and city dwellers moved to the suburbs. New houses included two-car attached garages, fast-food restaurants with drive-through service, suburban shopping malls and "Big Box" stores with acres of available parking. Highways widened and lengthened to help suburban dwellers attend city events and drive to other cities. The human footprint expanded, breaking up the wilderness. Fossil fuel consumption increased, and the planet's atmosphere warmed.

In a parallel chapter, Alves discusses Ohno's development "Lean" methods and the Toyota Production System which, combined with rising labor costs, led corporations to develop supply chains in lower-cost markets around the world. In *The Butterfly Defect* (Goldin & Mariathasan, 2014) discuss that:

> "Toyota was the first company to recognize that by leaving the production of individual parts to specialty suppliers they could optimize efficiency and operate more cost effectively. This quest for efficiency moved Toyota to open manufacturing facilities worldwide. The firm overcame geographic, linguistic, and cultural barriers to search out the most cost-efficient locations balancing production costs, speed to market, and access to labor. Lean Management has become the ubiquitous driving principle of globalized production."

Many companies, many industries, and many nations joined the "global value chain", and world-wide societal value increased:

> "The spreading of new technologies and systems around the world led to immense changes in how human beings interact and what they may achieve. Poor people have benefitted most; no era in human history has seen such a rapid reduction in the number of people in dire poverty, and the chances that the individual born into a poor family can escape poverty and live a long and healthy life are greater than at any point in history."

2000-2019: China's Growth in International Trade

As the Cold War ended, Chinese Premier Deng Xiaoping launched an economic revolution, opened his country to world markets, and saw an eight-fold increase in exports from 1999 to 2008. Wuhan, China saw benefits in joining the global value chain.

From the (Wikipedia entry on Wuhan, China):

> "Prior to the 21st century, Wuhan was largely agricultural, but since 2004 has been a focal in the "Rise of Central China Plan", which aims to build less-developed inland economies into hubs of advanced manufacturing.
>
> "The automobile industry is dominant in the region. There are 5 car manufacturers, including Dongfeng Honda, Citroen, Shanghai GM, DFM Passenger Vehicle Dongfeng Renault and Dongfeng-Citroen headquartered in the city. By 2016, Wuhan attracted foreign investment from over 80 countries, with nearly 6,000 foreign-invested enterprises in the city injecting $22.45 billion in investment. "

The region grew to include 19 million residents, has 35 higher educational institutions, is a hub in the nationwide high-speed train system, and has an international airport serving 20 million passengers. Wuhan expanded to accommodate growth in the global automotive value chain, and has transportation systems which allow people (and their infections) to move quickly around the world.

2020 and Beyond: A Systemic Pandemic

The region of southern China, Vietnam, Myanmar, and Laos are home to bats which for millions of years have hosted 'reservoirs' of coronaviruses, including SARS-Cov-1, which jumped to humans near Guangdong in 2003, and SARS-CoV-2, which jumped near Wuhan in 2019. Hundreds of millions of people are in proximity to highly mobile bats (Mckenna, 2020). Bats are particularly suitable hosts for viruses; their ability to fly allows them to control the inflammation which would afflict most mammals, and they become a near-perfect vehicle by which a viral reservoir can grow. Bats are not debilitated by the virus and can travel over one hundred kilometers a year.

Steven Soderbergh's 2011 film *Contagion* is the hypothetical story of a viral pandemic. In one scene, bulldozers knock down trees which scatter some bats, who fly above a pigsty and drop a half-eaten banana. A pig eats the banana, is slaughtered, taken to a hotel kitchen, and Gwyneth Paltrow's character picks up the virus in a chance encounter with the chef. The following day she flies to Chicago and infects the entire U.S. Early parts of the movie are highly analogous to the first weeks of the COVID-19 pandemic.

Infected humans on airplanes far outperform bats in term of viral spread. In previous centuries, endemics remained limited to a few thousand kilometers and would die out over time as humans developed immunity, but inter-continental travel is now easily available, and viruses can travel around the world in hours. SARS-CoV-2 (the virus which causes the COVID-19 disease) jumped to humans around December 2019 and infected all the world's ice-free continents by the following March.

By September 2020, SARS-CoV-2 was mutating into new variants which quickly made their way around the world, likely carried by infected passengers on aircraft. The (World Health Organization, 2021) identified four variants of concern, originating in (see Figure 2):

- Alpha: the United Kingdom, September 2020
- Beta: South Africa, May 2020
- Gamma: Brazil, November 2020
- Delta: India, October 2020

Thus, eighteen months after recognition of the original strain in Wuhan, new variants originating in four different continents are globally prevalent, indicating headwinds to economic recovery and air travel until the world develops immunity. Evidence of such headwinds is found in June 2021, as Britain's Prime Minister extended the U.K.'s COVID-19 restrictions due to the new dominance of the Delta variant, which originated in India just a few months earlier (Ansari & Douglas, 2021). The U.K. economy and public health had already been impacted by the original strain, as well as the Alpha variant, which originated there.

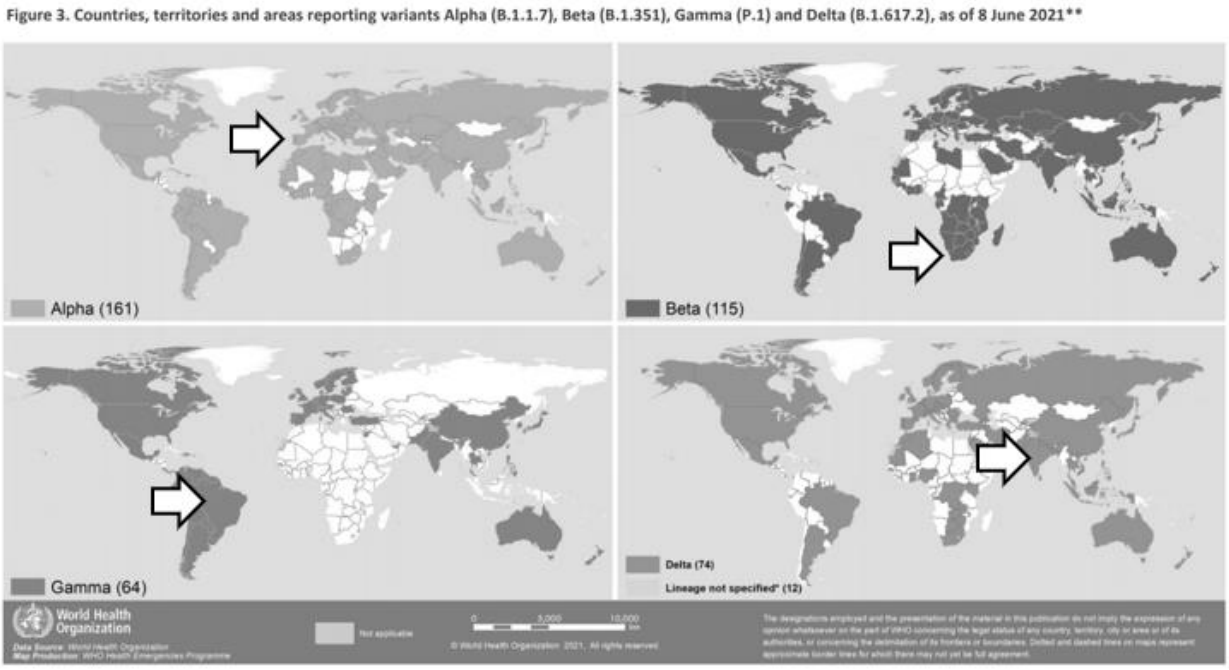


Figure 2: Variants of Concern Map (arrows indicate origin).

Settling the Biomes

In 1700, the one-billion humans living on the planet used only 5% of its ice-free surface, but over the next three centuries the population doubled three times (to eight billion) and leaves only a quarter of the surface as wild. (Ellis, 2010). While this chapter reflects primarily on the impacts of infectious viruses, it is inaccurate to view microscopic pathogens as the only threat. Aligned with the growth in globalization is the transmission of invasive species, such as:

- The **Emerald Ash Borer**, an inconsequential insect in its native region of north-eastern Asia has caused over $10B in damage in the U.S. Midwest and continues to spread. They likely arrived via shipping crates to Canton, MI. (Wikipedia: Emerald Ash Borer)

- **Zebra Mussels** are native to Russia and The Ukraine where they attached to ship anchor chains and have become invasive in the U.S. and Northern Europe. They are believed to be the source of an avian botulism which kills birds in the Great Lakes, responsible for the near extinction of many species, and lead to millions of dollars per year in cost to power plants and other water-consuming facilities. (Wikipedia: Zebra Mussel)

- The **Spotted Lanternfly** is native to China, India, and Vietnam but is now invasive in South Korea and the Delaware Valley of the U.S. It consumes over 70 plant species, including grape vines, fruit trees, and hardwoods like maple and birch. Per the USDA: *"If allowed to spread in the United States, this pest could seriously impact the country's grape, orchard, and logging industries."* (USDA: Spotted Lanternfly)

In the century past, which spans the Second Industrial Revolution, humans repurposed the wild, unintentionally living in ever-closer proximity to viruses and infections which they bring (Thomas, 2020).

Previously, threats to humans were lions, tigers, and bears, but expansion has now led to loss of habitat for these apex predators who would keep bats, birds, and rodents (and the reservoirs within) at bay. Humans have developed technology to move great distances in short times, quickly expanding what were once local reservoirs around the world.

Viruses mutate and evolve, and while thousands are catalogued millions are not. Sea-borne viruses increase oceanic respiration which reduces atmospheric carbon dioxide by 3 gigatons (Wikipedia: Viruses) per year, counteracting the 42 gigatons (McCarthy, 2019) currently emitted by industrial society. Viruses mitigate climate change; they are both beneficial and detrimental to human existence, and more to the point are an innate part of an environment in which humans must exist.

Pandemic frequency is increasing as humans encroach upon reservoirs, and humanity is on the cusp of a change not seen since the introduction of mass production a century ago. The 21st century has seen worldwide pandemics in COVID-19, Zika, MERS, Mumps, Swine Flu, and SARS thus far; five occurring in the past decade. (Wikipedia: List of Epidemics)

We should expect the 21st century to be a Pandemic Age.

Systems Thinking and Economic Disruption

In 1920 (and especially 1720), the wilderness seemed infinite, and the environment capable of absorbing the small burdens that humans placed upon it, but by 2020 humans consume too much of the earth for environmental and social impacts to be trivial. A field of thought, known as "Systems Thinking" is well-applied here, derived from two feedback loops as described by Donella Meadows in her book *Thinking in Systems* (Meadows, 2008), and Peter Senge in his, *The Fifth Discipline* (Senge, 2006). They each quote the other, and Meadows developed her theories based on studies of nature.

In **Reinforcing Loops,** growth in an element *encourages* more growth, fed by other elements. In an avalanche, a snowball dislodged at the top of hill rolls, picks up snow and boulders, which in turn pick up more snow and boulders. The loop reinforces itself until it consumes all available resources, in this case when the avalanche buries the ski chalets at the bottom of the mountain.

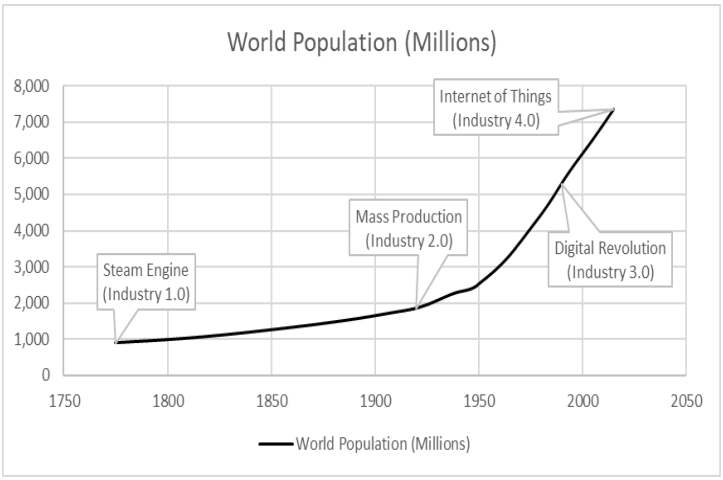
In **Balancing Loops,** growth in an element is *counteracted* by other elements, until an equilibrium is found. We see this in the price sensitivity of commodities; as a product becomes more popular its price rises, which makes it and associated goods less popular. The sale of gas-guzzlers counteracts the price of oil; as oil prices climb, SUV sales fall, and vice-versa.

Systems Thinking highlights that individual actions have systemic effect; our actions *create* our reality. The pandemics we face are not malicious and external but are the summation of smaller independent actions. The past century of economic growth has brought a net gain in societal value (Goldin & Mariathasan, 2014), but in the process placed burdens on environmental systems* which are now limiting human and economic growth. I'll discuss four such models.

* And social systems, though these are beyond the scope of this chapter.

Exponential Growth in Humans and Viruses

Reinforcing loops grow (and shrink) exponentially; a little growth makes a little more growth that much easier. In the Industrial Age, the introduction of the steam engine made life easier on humans, who used mechanization to grow more food and increase lifespans. This created opportunities for further innovation into mass production (the Second Industrial Revolution) which made life easier still. The human population grew exponentially, as seen in Figure 3. (Our World in Data)



A viral infection also grows and shrinks through systemic reinforcement. It originates as a tiny infectious agent which reproduces itself inside the cells of living hosts, at which point the host cell rapidly produces thousands of identical copies of the original virus. If it originates within a bat it will expand to a population of bats, then to a human (possibly via a pig, bird, or rodent), then the world-wide population of humans, and finally into bats, birds, pigs, and rodents on new continents.

Limits to Growth Models

Biological populations grow until they either consume all available resources or face some opposing force, which is known as "Limits to Growth" model (Figure 4). In the reinforcing stage of the model, people infected today will infect more people tomorrow, increasing the *rate* of growth. Humans are social creatures with a need to interact, giving the viral reservoir an opportunity to grow. Eventually humans retreat from the virus, either by diminishing transmission (e.g., social distancing) or diminishing susceptibility (a vaccine). Humans' neurological need to connect balances against the pathological risk of debilitating disease; as humans retreat, the reservoir diminishes, as it diminishes humans feel safe to gather, and the reservoir grows again. The number of active infections will rise and fall in waves.

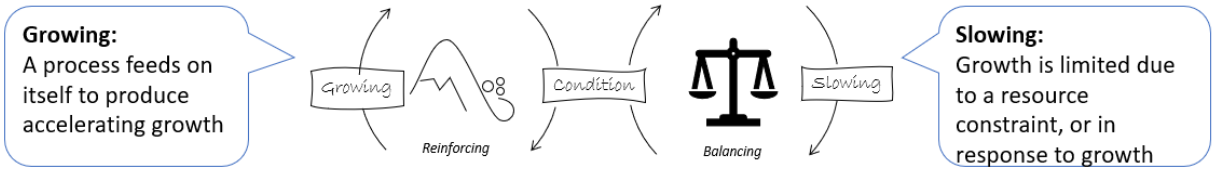


Figure 4: Limits to Growth

Figure 5 shows two such waves. The solid line is the sum of cases in New York, New Jersey, and Michigan, in which human hosts to the viral reservoir (aka "infected people") grew quickly in March and April. Those three states alone accounted for one-half of all U.S. infections, but they limited viral growth through mandates and societal norms and created a reinforcing decline. The dashed line sums all other states and shows the effect of not controlling a reinforcing loop early.

While by late August all states had slowed the growth of the viral reservoir, a month later infections increased as schools reopened. By January 2021, new caseloads in the U.S. exceeded 250,000 per day.

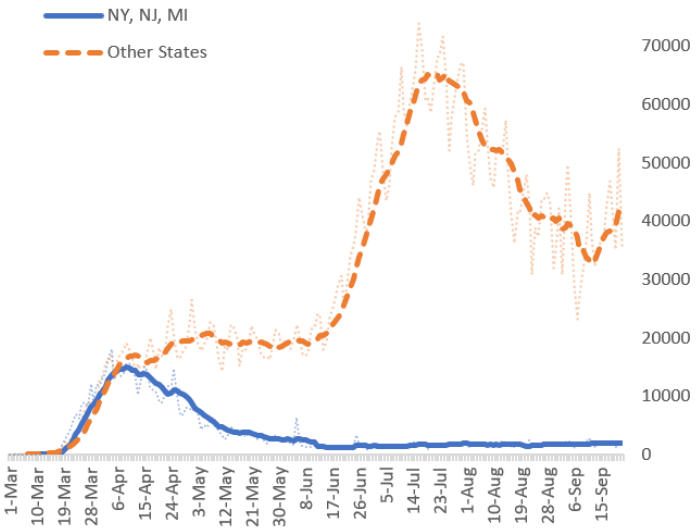


Figure 5: U.S Daily Cases
(New York Times Interactive:)

Shifting the Burden…

Senge describes a *"Shift the Burden"* model (Figure 6) where:

"An underlying problem generates symptoms that demand attention, but the problem is difficult to address because it is obscure or costly to confront. People "shift the burden" of the problem to other solutions – easy fixes which seem efficient.

Unfortunately, these easier solutions only address symptoms, leaving the problem unaltered. The problem gets worse though the symptoms apparently clear up, and the system loses whatever ability it had to solve the underlying problem."

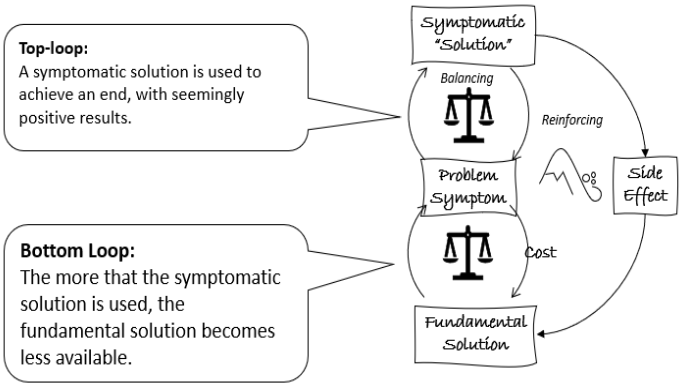


Figure 6: Shifting the Burden Model

From Figure 6 we can see two balancing loops; the bottom represents a fundamental solution (which will eventually be adopted) but is more time-consuming and costly than available symptomatic solutions. Choosing the symptomatic over fundamental solution becomes reinforcing, as it (seemingly) addresses relevant issues at low cost. But in doing so, the fundamental solutions become more difficult to achieve. Eventually, side effects lead to a reinforcing collapse upon the need for a fundamental solution.

Shifting the burden of manufacturing production onto a global value chain has enabled prosperity, eventually putting humans in contact with novel viruses, leading to a systemic public health collapse which diminishes prosperity. Fundamentally addressing a pandemic age requires decreases in both viral spillover and world-wide transmission of viruses after the spillover has occurred. The former requires retracting the human population footprint from wild spaces and allowing apex predators to flourish, the latter implies higher cognizance of public health as a condition of travel.

Following are three COVID-related examples of shifting production burdens:

… in Pharmaceutical Production

The Wall Street Journal reports (Yap, 2020) on production of over-the-counter medications like acetaminophen, an inflammation reducer. A key ingredient is phenol, which American pharmaceutical makers produced in Texas and Louisiana until around 2000, at which point they shifted their attention to high-margin blockbuster drugs and shifted the burden of bulk pharmaceutical manufacture into China. That nation had lower-cost chemists and manufacturing facilities, and now produces half of the world's active pharmaceutical ingredients (APIs), the ingredients in a pill that make it 'work'.

As SARS-CoV-2 expanded in China in January 2020, exports of acetaminophen to the U.S. declined by 70%. Chinese factories had closed due to employee quarantines or directed their production to meet local needs, leaving the U.S. with supply shortages when the drugs were needed.

Chinese exports picked up again in March and April, though one can make the case that this simply reinforces the symptomatic solution, making it that much more difficult to develop local U.S. production. In the article, Christopher Priest of the U.S. Department of Defense states "The national security risks of increased Chinese dominance of the global API market cannot be overstated."

… in Masks

By July 2020, the head of the US Centers for Disease Control estimated that "the pandemic could be brought under control over the next four to eight weeks if we could get everybody to wear a mask right now" (McCabe, 2020), at a time when the virus was known to be infecting 65,000 new patients per day. Imagine the value of even fewer masks at the time the pandemic was first identified in mid-March, when the new daily case rate was less than 1,000. Mask-wearing could have limited early growth of the viral reservoir and put it into a reinforcing decline, such as the New York, New Jersey, and Michigan chart in Figure 5.

Studies show that viral particles can "float" as an aerosol in closed spaces and permeate the entirety of a small room within minutes. A mask-wearing person (even a simple cloth mask) decreases aerosol spread. Masks are inexpensive, do not require months or years of research as is required of a vaccine, and have little in the way of negative side effects.

Medical staff use special "N-95" masks to protect themselves as they work in viral-laden environments, but these were in short supply in the early weeks of the U.S. pandemic. Lean management metrics used by hospitals encouraged low inventories and low unit cost, leading them to buy inexpensive masks from overseas "just in time". As with acetaminophen, by the early 2000's ninety percent of N-95 mask production had shifted to low-cost providers overseas. (Davis, 2020)

In 2009, the company Prestige Ameritech was one of few remaining U.S. companies capable of manufacturing N-95 masks. The H1N1-09 "swine flu" pandemic was on the horizon, Prestige increased production to meet the expected need, but that pandemic quickly ended, N-95 demand collapsed, and the company nearly went bankrupt. The symptomatic solution in which hospitals purchase masks from low-cost suppliers throughout the global chain was "working"; the U.S. survived the 2009 swine flu and 2003 SARS-1 pandemics without the need for local mask production. There was no perceived need for a more fundamental solution.

In 2019, as SARS-CoV-2 appeared, Prestige again recognized the impending risk and reached out to the U.S. Department of Health and Human Services to seek funding to restart their 2009 production lines. (They did not want to face bankruptcy again.) But HHS did not follow through with an offer, Prestige's manufacturing capacity of 7 million masks per month remained idle, even though medical staff were infected (in many cases fatally) in the early days of the U.S. pandemic.

A new symptomatic solution appeared in late April as large manufacturing companies (including the automaker General Motors) began making masks and ventilator equipment. If the most fundamental solution to supplying N-95 masks to hospital staff is to minimize distribution risk, (for example, by manufacturing the masks on the hospital campus) the U.S. seems a long way off.

… in Management Theory

From *The Butterfly Defect* (Goldin & Mariathasan, 2014):

> "The prevailing logic of supply chain management today is that the production of goods, where possible, should be outsourced to the most cost-efficient provider, and the homogenization of management education (in MBA programs) … cements the spread of practices like lean management and outsourcing.
>
> "But it also leads to an over-reliance on a homogenized box-checking approach to risk management. As students in emerging Eastern Universities learn the techniques of their Westernized counterparts, and vice versa, it facilitates the spread of monocultures."

As industries and schools throughout the world align on a single set of practices, diversity of thought diminishes, and a monoculture develops. As all practitioners follow one approach, they become unable to recognize the failings in that approach. The systemic failure in modern management theory is that it *does not* advocate for individual companies to demand increased public health spending.

The "single-bottom-line" metrics of the airline, theme park, sports stadium, hotel, and restaurant industries (among others) rely on a healthy populace, but they do not take on the burden of general public health. Had airlines invested $100 million in stockpiles of personal protective equipment, they may have saved billions in lost revenues. Or they could have advocated for (and willingly paid) higher taxes so that governments would take on the public health responsibility. Calling for higher taxes and/or supporting high inventories of hundreds of millions of unused masks seems financially inefficient for an airline… except in comparison to the market collapse which they now face.

This is not to fault past decision-makers, but to highlight the systemic nature of risk in running their companies based on mass, lean, and single-bottom-lines; the mainstays of the Second Industrial

Revolution. A triple-bottom-line management philosophy, which includes the needs of People and Planet, as well as to Prosperity, is needed to reduce future economic collapses.

The fundamental solutions to exit this Pandemic Age may be to:

- Diminish viral spillover by avoiding reservoirs and allowing wild spaces and apex predators to flourish.
- Minimize the transportation of pathogens and invasive species through reshoring supply chains.
- Increase public health to defend against new viruses and other biological invaders.

These will be discussed in the following section.

Tragedy of the Commons

Donella Meadows supplies the following example in *Thinking in Systems*:

"Imagine a common pasture open to all herders. Each will try to keep as many cattle as possible in these commons, and will independently ask "what is the benefit vs. utility of me adding one more animal to my herd?" The benefit is the entire proceeds gained by one cow, while the cost of overgrazing is shared by all. The rational decision for each herder is to continue to add to their own herd, without regard to systemic collapse."

Senge diagrams this as in Figure 7. Organization's "A" and "B" each gain independently from their own activity, though the activities draw from a common depletable resource. Decisions made by "A" and "B" are locally rational, but eventually lead to systemic failure.

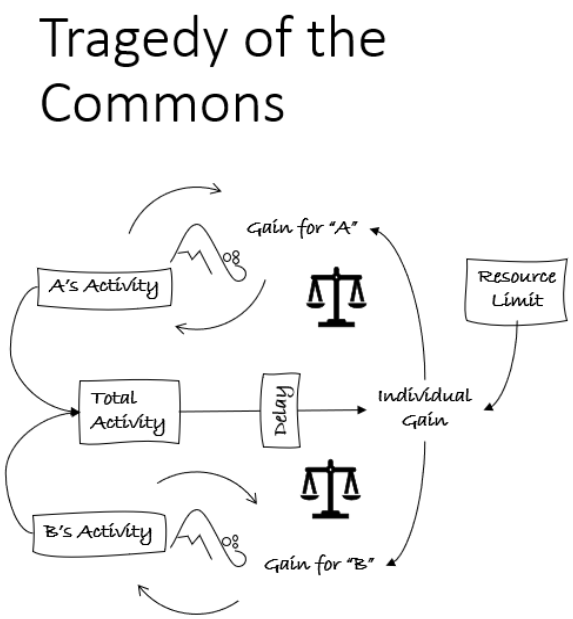


Figure 7: Tragedy of the Commons

… in Lobster Fishing

A historical example of this in lobster fishing off the coast of Maine (Mills), where each boat attempts to maximize its own catch, with the systemic result of depleting all available lobsters. Tragically, depletion of fisheries in the 1990's led to bankruptcies and economic suffering for not only the lobstermen, but the surrounding towns as well.

Through fisheries management lobsters came back to the coast of Maine (Maine.gov), and fishermen and governments developed cooperative mechanisms to limit individual activity in pursuit of maximizing regional goals. Maine is a popular tourist destination, and all businesses benefit when a steady flow of lobster is available. Local banks take on a systemic risk across the regional economy as they make loans

to restaurants, hotels, and gift shops. While for each fisher it is economically rational to acquire as many lobsters as possible, for local banks and the larger economy it is rational to insist on sustainable practices in lobstering. The local economy is interconnected, and banks have the greatest visibility; local leaders recognized the System of Systems which make up the Maine economy, and created financial leverage to accomplish systemic goals.

Global Investing to Manage Systemic Risk

In SARS-1 and SARS-2, the world suffers the fate of the Tragic Commons story. Mass, Lean, and single-bottom-line financial metrics led to industrialization near the habitat of viral-laden bats near a growing human population in southern China. Nearby airports accommodate millions of international passengers per year, many in support of a global supply chain. Infected passengers unwittingly allow the viral reservoir to expand across continents and push worldwide economies into recession, collapsing the chain. Industries have a common need for public health; tragically none has an economic rationale to invest in it.

Large institutional investors such as BlackRock, Vanguard, State Street, and CalPERS, with trillions under management, recognize that they are too big to avoid systemic risk. For example, BlackRock, the world's largest asset manager, announced in January 2020 (prior to COVID-19 reaching pandemic status) that it will make its investment decisions with environmental sustainability as a core goal. In the firm's annual letter to investors, CEO Larry Fink wrote: "The evidence on climate risk is compelling investors to reassess core assumptions about modern finance…", and "Awareness is rapidly changing, and I believe we are on the edge of a fundamental reshaping of finance". (Sorkin, 2020) Similarly, Anne Simpson, managing investment director of the California State Pension Fund: "if you're facing systemic risk, you can run, but you can't hide. In other words, we can decide not to invest in a company that's producing emissions … but if the emissions continue, we're still exposed to the risk of climate change" (Aguirre, 2021).

A New Economy for the Fourth Industrial Revolution

Mass-production and the second industrial revolution enabled reinforcing economic growth, which now faces limits as humans overlap with viral reservoirs. The 21st century has already seen multiple pandemics, we can expect more in the coming decade, and are on the cusp of financial and technological changes known as the Fourth Industrial Revolution. The (World Economic Forum, 2020), a '4IR' leader, calls for corporate purpose to expand beyond "shareholder capitalism" and towards "stakeholder capitalism", in which the corporation is "responsible to the Environment, Society and Good Government" (known as ESG). This is a System of Systems approach, where the systems are financial, social, and environmental.

To date, there are no easy means to measure the social and environmental functions, but interested parties begin to align. In an August 2019 release (Business Roundtable Redefines the Purpose of a Corporation) , 181 CEO's including those of GM, Boeing, Bank of America, and BlackRock, signed a corporate governance agreement that *"moves away from shareholder primacy and includes a commitment to all stakeholders"*. Over 3,000 investment firms, representing over $100 Trillion in assets under management, are signatories to the (United Nations: Principles of Responsible Investing)

initiative which *"acts in the long-term interests of the financial markets and economies in which they operate and ultimately of the environment and society as a whole"*.

Weeks prior to the COVID-19 pandemic, the (International Business Council, 2020), headed by the CEO of Bank of America, issued a similar statement to encourage discussion of proper metrics:

> "…it is important to consider environmental impacts along the full value chain (or 'lifecycle') of products or services. Individual businesses often operate in a small section of the overall value chain … but they rely on the continuing commercial viability of all upstream and downstream parts of the chain to sustain their own commercial success."

To again quote *The Butterfly Defect* (Goldin & Mariathasan, 2014):

> "The underlying threat of globalization on a systemic level pertains to the formation of harmonized structures and a failure to ensure 'resilience', the capacity of a system to absorb disturbance and reorganize while undergoing change."

Harmonized structures include businesses behaving in Tragic Commons scenarios, in which each act according to their own business metrics without recognizing unmeasured impacts on and from the larger systemic environment. Upstream and downstream risks cross industry and international boundaries in unexpected ways; while Wuhan's economy developed to support the global automotive value chain, a nearby viral reservoir creates existential risk for the world economy, across many industries. Century-old businesses interconnect in ways unimaginable to their founders; to minimize systemic risk, we need new economic and industrial systems.

I described a few here:

Supply Chain Resilience

Globalization has led to long and 'opaque' supply chains; where manufacturers buy components from 'first-tier' suppliers, who in turn buy sub-components from 'second-tier' suppliers, and on and on, with little visibility between tiers. Even prior to the 2020 pandemic, multinational corporations (MNCs) recognized systemic supply-chain risk between themselves and first-tier suppliers and created standards which they expected to cascade down onto the lower tiers. But the effect of these standards on the chain has thus far been limited. (Villena & Gioia, 2020) discuss:

> "The aim to create a cascade of sustainable practices that flows smoothly throughout the supply chain is hard to realize in practice. Many of the corporations that have committed to it have faced scandals brought about by suppliers that, despite being aware of sustainability standards, have nevertheless gone on to violate them.
>
> "Lower-tier suppliers often do not have sustainability expertise or resources, and they may be unaware of accepted social and environmental practices and regulations. They are frequently located in countries where such regulations are nonexistent, lax, or not enforced at all. And typically, they don't know much about the sustainability requirements imposed at the top-tier —and have no incentive to comply."

Further, top-tier corporations handicap themselves through dysfunction and uncoordinated goals. They often don't know who or where their lower-tier suppliers are, let alone their capabilities. Sub-groups within the MNC make key decisions without sustainability or compliance in mind.

> Top-tier engineering and procurement units often pre-approve lower-tier suppliers, but their vetting criteria doesn't include social and environmental considerations… Not surprisingly, this leads to situations in which pre-approved lower-tier suppliers violate the sustainability requirements of the top-tier consumers they work with.

Engineering and procurement groups may have de facto authority to drive lower-tier purchasing decisions based on *unit* cost (affecting profits), without regards for *environmental* or *social* costs (affecting planet and people). This is a Tragic Commons scenario, where locally rational decisions within the MNC lead to systemic failures.

Localizing Supply Chains

'Short' supply chains are less opaque and will become more valuable as nations become cognizant of the risk of transporting diseases and invasive species, and how long can corporations maintain buyer-supplier relationships if the former is unable to visit the factories of the latter? Fifty-six percent of U.S. intermediate imports (components needed for the manufacture of larger products) are sourced from China, Mexico, Canada, Germany and Japan (International Analytics Website, 2021), and even 18 months after the virus was first recognized, the U.S. State Department's (Travel Advisories, 2021) specifies "Level 3: Reconsider Travel", for each of them. What was formerly a 2-hour trip between Detroit, MI and Windsor, ON requires 2-week quarantines on either side (Canadian Travel Restrictions, 2021). Restrictions and individual safety concerns become sand in the gears of the worldwide economy.

Aircraft and automobiles include thousands or millions of parts from dozens of countries; if a U.S. auto assembly plant can't get tires from Brazil, it won't need engines from Canada. The $20 Trillion U.S. economy imported over $3 Trillion in intermediate components (McBride & Chatzky, 2019); as import frictions rise, the lost opportunity due to unavailable components will increase. All industries leveraging a global value chain will face similar issues as discussed previously with N-95 masks and pharmaceuticals.

Industry 4.0 Technologies

Early in the pandemic the United Nations (Seric & Winkler, 2020) researched supply shortages in ventilators, and how Industry 4.0 technologies might in the future provide relief:

> "One of the main bottlenecks in the current production of ventilators is the timely supply of components due to dependence on inputs produced by global suppliers. Instead of producing the entire product from scratch, countries specialize in different tasks resulting in high interdependencies. One of the leading manufacturers of ventilators declared that it would double its output (in weeks, but) it relies on its wide network of closely integrated global suppliers for continuing its operations, including timely production of electrical components such as circuit boards or sensors.
>
> "Industry 4.0 unlocks new labor-saving technologies which could potentially reduce reliance on low-skilled, low-cost labor in manufacturing. This has implications for the global geography of

production, as value chains can be expected to become more regional in nature, moving closer to key final consumer markets in China, the European Union, Japan and the United States. Industry 4.0 is also likely to have an impact on the length of value chains, as automation could consolidate various steps of the value chain."

"Several factors seem to support the argument that automation and possibly reshoring will accelerate following the COVID-19 pandemic. The case of testing in the Republic of Korea exemplifies that automation facilitates supply-side adjustments (e.g., through on-demand ordering), mitigating firms' risks in case of a pandemic or other shock, as it allows for more flexible adjustment to increasing demand. In an effort to reduce countries' dependence on global supply, industrial policies to secure the supply of goods deemed critical to the healthcare sector and national security could be implemented."

The increased use of automation implies a need to upskill workforces, which is discussed shortly.

Digitalization and 'Pop-Up' Vaccine Factories

An important use of digitalization is in supporting the manufacture and distribution of vaccines and treatments as they are developed. The Pfizer-Biontech vaccine was approved in December 2020, just 10 months after a pandemic was declared (Thomas K. , 2020), and six months later three billion doses have been administered globally, less than 1% of those in low-income countries (Our World in Data, 2021). But the worldwide potential for a COVID-19 vaccine is ten billion or more units per year,[†] of a perishable and life-saving product. Doses require either an injection or inhalation device, implying the need to manufacture, store (at very cold temperatures), distribute, and dispose of large quantities of metal and plastic.

Rather than a few large, multi-billion dose factories, a more fundamental solution will be to build smaller factories near population centers which consume the vaccine, syringes, and inhalers. If we arbitrarily assume one factory per five hundred million people, it implies the need for 100 vaccine production factories scattered throughout the world.

Digital Manufacturing Twins

In Henry Ford's time it made sense to assemble all the world's automobiles in Detroit and transport them world-wide, because knowledge in how to manufacture thousands of cars per day was local to the region. But in the world of 4IR, we can *transmit* digital information about automated manufacture, rather than *transport* physically manufactured products. Modern industries design and simulate their products and factories using 3D virtual models; this can and should be applied to vaccine manufacturing.

The concept of a "Digital Twin" is that every physical thing inherently holds information about that thing, such as its size, mass, center of gravity, and chemical or electrical properties. By separating the information model from the physical instance, we can with little effort transmit the information model anywhere in the world. Modern products are developed by first using computer-aided design (CAD) software to establish dimensions, calculate mass, and simulate how the physical object will behave in

[†] The math: The human population in 2020 is about 7.8 billion. There many unknowns, including duration of immunity, the percentage of recovered or inoculated people required for herd immunity, and the number of doses per year needed for inoculation. If 70% of the world needs two doses per year, it's roughly 10 billion doses.

the environment. The software can even determine how much mass can be placed on the product before it collapses, how it behaves in a crash, or how it would behave in a windstorm. (Grieves, 2011)

A Digital *Manufacturing* Twin begins with the virtual instance of, say, a vaccine manufacturing plant which is shared around the world so that physical vaccine *factories* can be easily replicated. These would manufacture vaccines locally for nearby populations of maybe 500 million people. Each of the hundred physical plants could be identical, as they are based on the same virtual model.

An example currently exists in two Siemens electronics plants, one in Amberg, Germany and the other in Chengdu, China:

> "We mapped the processes from the Amberg plant to Chengdu on a 1:1 basis," explains Dr. Gunter Beitinger, who is responsible for Siemens' Digital Factory Business Units in Amberg, Fürth and Chengdu. From its machinery and software tools to its execution system which records and controls every aspect of the production process from start to finish at a virtual level, the equipment in Chengdu is designed on the same principles and processes as the equipment at the Amberg factory. (Siemens Corp.)

To greater and lesser extent, aircraft manufacturers have adopted digital twin strategies[‡]. The airline industry is improved by the worldwide distribution of vaccines and treatments, and aircraft manufacturers might explore new business units around the design and build of vaccine manufacturing plants.

And there is an ecological benefit as well, which may dwarf the others. Global shipping produces nearly 3% of global carbon-dioxide emissions, equivalent to the entire continent of South America (Almendral, 2021). Transmitting manufacturing know-how to a Digital Factory Twin, rather than transporting physical goods, could play a significant role in reducing greenhouse gasses.

Impact on Workforces

A pre-pandemic study by (The Manufacturing Institute, 2018) showed that the U.S. would need 15 million skilled manufacturing workers to meet the manufacturing needs of 2028, and only ten million people of that workforce were members of the 2018 workforce. Further, the advanced manufacturing skills of the Fourth Revolution become quickly obsolete, with only 50% of technical skills still relevant after five years. This implies that of the 10 million workers in 2028 who will have a decade or more experience, only 25% of what they knew in 2018 will still be relevant. Of the remaining five million positions, 2.6 million positions will go unfilled for lack of workers with the necessary skills.

And this was prior to the need to re-shore supply chains and build vaccine factories.

This follows a "Shift the Burden" model, in which the burden of manufacturing the world's goods moved to low-cost regions, and the U.S. no longer has workers with necessary skills. As industries re-shore supply chains, there will be increased demand for flexible workforces skilled in automation. Businesses must actively focus on creating and improving skills in their current and future workforce if they hope to survive. Among other goals, tuition burdens for post-secondary education will need to shift from students and their parents to employers.

[‡] Earlier in my career, I helped them with this

Viral Monitoring

To decrease viral spillover, we must retract from viral reservoirs, but we must also assume that new viruses will continue their jump to humans. Viral growth is reinforcing, limiting it early can stop viruses before they become pandemics.

IoT Thermometers

The "Internet of Things" is a large and growing concept that non-computers ("things") might be connected to the internet. The company Kinsa sells thermometers which connect to the internet.

Fever is a potential symptom of COVID-19, and when people feel sick, they take their temperatures with Kinsa thermometers. The company collects this and posts anonymized fever data to a "health map" on their website, healthweather.us. and can predict when flu-like illnesses will appear around a week before patients call their doctors. In this scenario the number of feverish people in a region could call for localized lockdowns (rather than state or county-wide lockdowns). If it becomes a norm to have one's temperature taken upon entering a building, this can also provide an important source of data.

(Note that body temperature is not conclusive; recent evidence shows that asymptomatic carriers of the SARS-CoV-2 virus do not have fevers. But we should prepare for more viruses.)

Sewage Monitoring

From the UK's Centre for Ecology and Hydrology: (Williams, 2020)

> "Scientists will develop a standardized UK-wide system for detecting coronavirus in wastewater, to provide an early warning of future outbreaks and reduce reliance on costly testing of large populations.
>
> "Several studies have shown that the RNA of SARS-CoV-2 - the genetic material of the virus - can be detected in wastewater ahead of local hospital admissions, which means wastewater could effectively become the 'canary in the coal mine' for COVID-19 and other emerging infectious diseases.

American Universities are following similar methods. R.I.T, in Rochester, New York, and the University of North Carolina, Charlotte are collecting samples from residence hall sewage lines. Automated means of testing samples are on the near horizon.

Similar to the IoT Thermometers, sewage monitoring could provide localized recognition of this and future viruses. Sewage has an advantage over the thermometers in that it can recognize the virus in a population which does not feel sick enough to take their temperature.

Individual Testing

Sewage monitoring and in-home temperature collection can identify communities in which the virus exists, to be followed by individual testing. South Korea accomplished this at mass scale in, as reported by the United Nations Industrial Development Organization (UNIDO) (United Nations Industrial Analytics Platform , 2020):

> *"[South] Korea is using Industry 4.0 technology to test far more people for COVID-19 than has been possible in many other countries and has thereby successfully limited the number of deaths linked to the virus. The Korean company Seegene, which carries out multiplex molecular*

diagnostics, relied on its artificial intelligence-based big data system to develop a test for COVID-19 within a few weeks, a procedure that usually takes several months to complete. Quick approval by the Korea Centers for Disease Control and Prevention within less than one week ensured that testing for COVID-19 was up and running. Moreover, Seegene's system uses automatic testing, i.e. samples are analyzed by a diagnostic machine rather than by humans, which speeds up the process and reduces risk of error and contamination."

Conclusion

A weekly family Zoom call (a result of the pandemic) in September 2020 included two households living near Seattle. Three of their college-age kids had been forced home from Florida, Wisconsin, and California due to COVID-19, and were "attending" classes remotely. Further, no one in either household could exit their homes for long periods due to smoke from fires which are burning hundreds of miles away, and likely to recur yearly.

Is this the society that we want?

The system of systems which humans inhabit is subordinate to the system of nature. Trillion-dollar asset managers are recognizing that a century of Industry 2.0 has created systemic risks which they are too large to avoid. Economic incentives in new product development (and current product replacement) must fit within sustainability goals.

I teach a graduate course in Engineering Management and my students are millennials born around 1990. They were graduating high school as financial markets collapsed in 2009, and expected to buy houses and plan families as the COVID-19 recession appeared in 2020. In financial crises over the past two centuries, it has taken a median of seven years for per-capita GDP to return to pre-crisis levels. (Reinhart & Reinhart, 2020) Millennials also face high student loan debt, and the increasing impacts of climate change. For their own security and to improve their quality of life they will search for new economic means by which they measure success.

In spite of (or maybe because of) these challenges I see in my students a group who will transform industry and economy in ways not seen in the century since Henry Ford. Our current decade is not starting at all well, but I expect by its end we will see a strong advancement into new measures of industry and economy, based on the triple bottom lines of People, Planet, and Prosperity.

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