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Stumbling towards Sustainability:

Why organizational learning and radical innovation are necessary to build a more sustainable world—but not sufficient

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Abstract

Our civilization is unsustainable and it is getting worse fast. The human ecological footprint has already overshot the sustainable carrying capacity of the Earth, while population and economic growth are rapidly expanding our impact. Meeting the legitimate aspirations of billions to rise out of poverty while reducing our global footprint to sustainable levels is the defining issue of the age. Change and transformation are urgently needed throughout society. But how can such change be achieved? Here I offer a dynamic systems perspective to raise questions about the processes of change required, at multiple scales. Within organizations, process improvement initiatives directed at cost, quality and productivity commonly fail. Sustainability initiatives share many of the same attributes. Why do so many such programs fail and what can be done to improve them? At the industry level, many attempts to introduce radical new technologies such as alternative fuel vehicles exhibit "sizzle and fizzle" behavior. Why, and what can be done to create markets for radical new technologies that are sustainable ecologically and economically? At the level of the economy, does it all add up? If firms are successful in "greening" their operations and products, does it actually move our economy towards sustainability, or simply lead to direct and indirect rebound effects? Technological solutions promoting ecoefficiency and new, sustainable industries, while necessary, are not sufficient: as long as everyone wants more, there is no technical solution to the problem. Where, then, are the high leverage points to implement successful change programs in existing organizations, create new industries, address overconsumption and transform personal values?

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Our civilization is unsustainable and it is getting worse fast. Humans now appropriate 38% of net primary production. Most of the rest is unavailable, leaving only 9% for future growth. Humanity has exceeded sustainable boundaries for greenhouse gases (GHGs), nitrogen, biodiversity loss, and other critical resources and ecosystem services. The ecological footprint of humanity is now 1.5 times the sustainable carrying capacity of the Earth.[1] At the same time, population is expected to grow by 2 billion by 2050 and consumption per capita is growing exponentially. Reducing our global footprint to sustainable levels while population grows and billions around the world legitimately aspire to rise out of poverty is the defining issue of our time.

Meeting the challenge requires rapid change and transformation throughout society. But how can such change be achieved? Here I offer a dynamic systems perspective to raise questions about the processes of change required, at multiple scales.

At the organizational level, firms are implementing improvement programs to cut energy and resource use, reduce waste generation, design more sustainable products and services, and so on, often with the expectation that they can do well by doing good: simultaneously reducing costs and environmental impact. Yet research shows that traditional process improvement initiatives directed at cost, quality and productivity commonly fail. Sustainability initiatives share many of the same attributes. Why do so many such programs fail and what can be done to improve them?

At the industry level, many attempts to introduce radical new technologies such as alternative fuel vehicles exhibit "sizzle and fizzle" behavior. Why, and what can be done to create markets for radical new technologies that are sustainable not only ecologically but economically?

At the level of the economy, does it all add up? If firms are successful in "greening" their operations and products, if new, more sustainable industries arise, will they actually move our society towards sustainability, or will greater consumption overwhelm ecoefficiency?

To begin, consider programs designed to promote sustainability within existing organizations.

Sustainability as Product and Process Improvement

Nearly all firms now seek to reduce their greenhouse gas emissions, energy consumption, and waste generation in the name of sustainability. Initiatives to reduce a firm's environmental impact, improve labor practices and ethical sourcing, and develop more sustainable products and services can be usefully analyzed through the lens of process improvement programs. The primary difference is that traditional improvement initiatives are justified and marketed to employees, supply chain partners, customers, and investors as critical for competitive advantage, profitability, or firm survival—that is, they are seen as central to the core business—while sustainability initiatives are framed as (also) helping to heal the world.

Across nearly all industries and firms, the unit costs of production, product capabilities, and other product and process attributes steadily improve through learning by doing, investment in R&D, assimilation of feedback from customers, and other means.[2] The rate of learning in any process can be characterized by its *improvement half-life*, the time required for defects in any process to be cut in half. The concept of "defects" includes any characteristic of a process that leads to waste or error, including product defects, safety incidents, unit costs, process cycle times, and other traditional business metrics, as well as energy consumption, pollution, solid waste generation, and other metrics relevant to sustainability. Figure 1 shows two examples with very different half-lives: the manufacturing cycle time for an electronics assembly plant in the auto industry, and the number of traffic fatalities per vehicle mile traveled in the US.

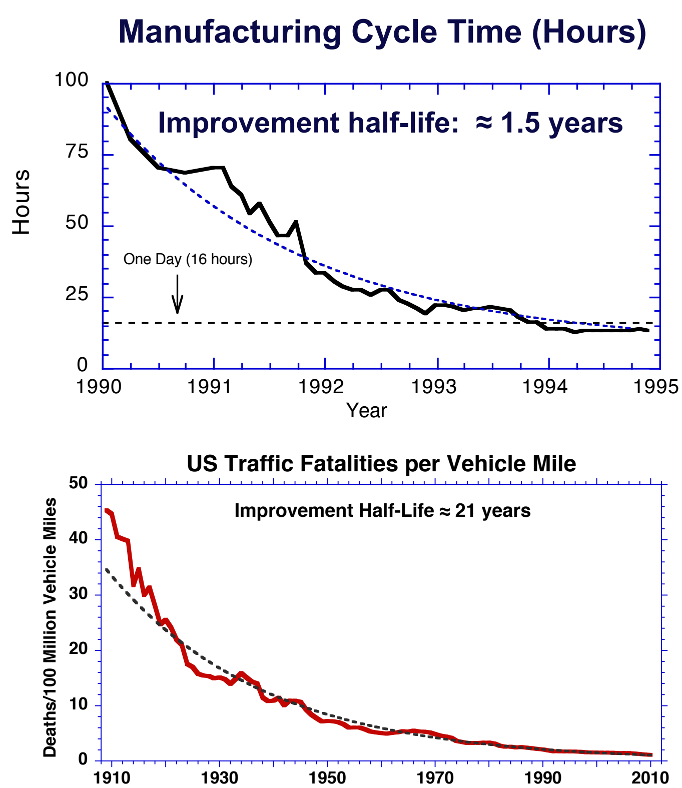


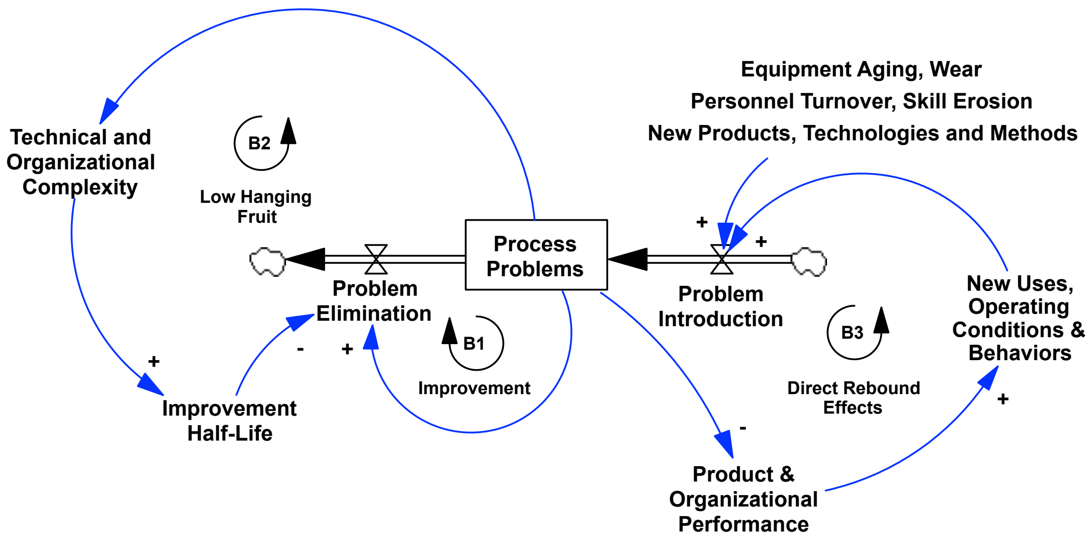
Figure 1. Improvement and improvement half-life in two processes. Top: Manufacturing cycle time in an electronics assembly plant. Bottom: US Traffic fatalities per VMT.

After the assembly plant initiated an improvement program, the manufacturing cycle time fell rapidly, from over 100 hours to about 16 (a single two-shift workday), with an average improvement half-life of only about 1.5 years. In contrast, US auto fatalities fell from a peak of 45 per 100 million vehicle miles traveled (VMT) in 1909 to about 1.1 per 100 million VMT by 2010, an average improvement half-life of about 21 years.

What accounts for the difference in improvement half-lives? Improvement arises from an iterative process in which workers search for and experiment with new ways of carrying out tasks, select and adopt the best ones, then search for additional improvements.[3] The iterative process of search, trial, evaluation and adoption of improvements can be informal and tacit, or take place in the context of a formal improvement methodology such as Six Sigma.

Figure 2 shows the core feedback structure governing improvement processes. The stock of process problems—the total number of root causes generating defects, waste or errors of any type—is decreased by improvement and increased as equipment ages and wears, as personnel turn over and skills are lost, and as new products, technologies and methods are introduced. If problem elimination from improvement exceeds the creation of new problems then the stock of process problems will fall, boosting the performance of the organization's products and processes. The larger the stock of process problems, the greater the effort to improve, forming the balancing (negative) *Improvement* feedback labeled B1 in Figure 2. How fast can that improvement occur? Whether formal or informal, the improvement half-life for any process is determined by the cycle time for each iteration of the learning cycle and the fractional improvement achieved per cycle. The faster the cycle time and the more learned per cycle, the shorter the improvement half-life (Figure 2).

Improvement half-lives vary across processes and over time. Sterman *et al.,* following Schneiderman,[4] argue that improvement half-lives increase with the technical and organizational complexity of the process. Technical complexity is straightforward: improvement will be faster for a simple milling machine than for the tooling used to fabricate the wing for the Boeing 787. Organizational complexity refers to the number of different personnel, organizational functions and levels, and organizations that must be involved to improve the process. Improving the milling machine requires only a few people—the operator, perhaps a mechanic—while improving the 787 wing requires the active participation of labor from multiple crafts, engineers from many different disciplines inside Boeing and from its suppliers and tooling vendors, and the managers in each of those organizations required to coordinate the process. Improvement half-lives are on the order of a few months for processes with low technical and organizational complexity, but several years or more for processes with higher complexity such as product development or vendor-supplier relationships.[5]



The stock of problems in any process represents the root causes of all sources of defects, waste and error. Process problems are eliminated by learning and process improvement. The stock of process problems, P, is governed by

$$dP/dt = \textit{Problem Introduction} - \textit{Problem Elimination} = \textit{Problem Introduction} - \phi\,(P - P_{min})$$

where $P_{min} \geq 0$ is the minimum possible problem level and ϕ, the fractional improvement rate, is determined by the improvement half-life, $\phi = \ln(2)/t_h$. If the improvement half-life is constant, the level of process problems falls exponentially. Improvement will be slower than exponential when the improvement half-life rises with increasing process complexity, as shown by the balancing *Low Hanging Fruit* feedback B2.

Figure 2. Core feedback structure of process improvement.

Considering the examples in Figure 1, the technical and organizational complexity of the electronics assembly plant is low: cutting the manufacturing cycle time involved improving the reliability and quality of relatively simple equipment and processes. Doing so required the participation of relatively few workers, engineers, and front-line managers, all from the same facility. In contrast, automobiles are technically complex, with tight couplings among major subsystems including drive train, brakes, suspension, sensors and controls, and between the vehicle and driving environment, including road design, signage, traffic conditions and driver skills. Organizational complexity is even higher: modern automobile product development involves hundreds of engineers from multiple backgrounds, along with people from marketing, production, procurement, finance, environment, legal, and other departments, and representatives of component suppliers from tires and glass to airbags and telematics. Coordination among auto companies also affects the pace of improvement. Working sometimes with, and sometimes in opposition to, their rivals, governments, the insurance industry, physicians, and citizen groups, automakers have shaped technology, regulations and legislation affecting safety such as seat belts and air bags. Such high technical, organizational and political complexity leads to a much longer improvement half-life for automotive safety compared to process improvement within a plant.

Figure 3 qualitatively maps different sustainability issues into the space of technical and organizational/political complexity. Many energy efficiency and waste reduction programs, for example, have very low complexity on both dimensions, and there are many such opportunities with very short payback times, high ROI, and positive net present value.[6] Alternative energy projects such as wind turbines and solar photovoltaics have higher technical and organizational complexity—insulating your attic is often a DIY project, while installing a solar PV array on your roof involves PV module suppliers, an architect or contractor, installers, and local governments who permit and inspect the work. Greening a firm's supply chain is technically challenging due to the need to consider life-cycle impacts of the entire process from raw materials to disposal/recycling, and organizationally challenging as the focal firm must partner effectively with multiple tiers in increasingly global supply networks. Creating a low-carbon automobile fleet involves envelope-pushing technical complexity but also requires society-wide coordination among automakers and their supply chains, fuel providers, governments, and other actors required to build critical complementary assets including fueling infrastructure, to develop consumer awareness and acceptance of new technologies, and so on (see below). Ethical production including decent wages and healthy, safe workplaces is technically simple—there is no technical challenge in providing fire alarms and emergency exits in garment factories—but involves coordination across retailers, suppliers, unions, labor activists, NGOs, governments, and others in a global economy.[7] Sustainable management of common pool resources such as forests, fisheries and the climate involves moderate technical complexity, but very high organizational and political complexity, often requiring multi-scale, polycentric governance extending from the community level to the global level of international agreements and treaties.[8] Finally, reducing overconsumption is technically simple, but raises contentious social and political issues rooted in difficult questions about the meaning and purpose of our lives.

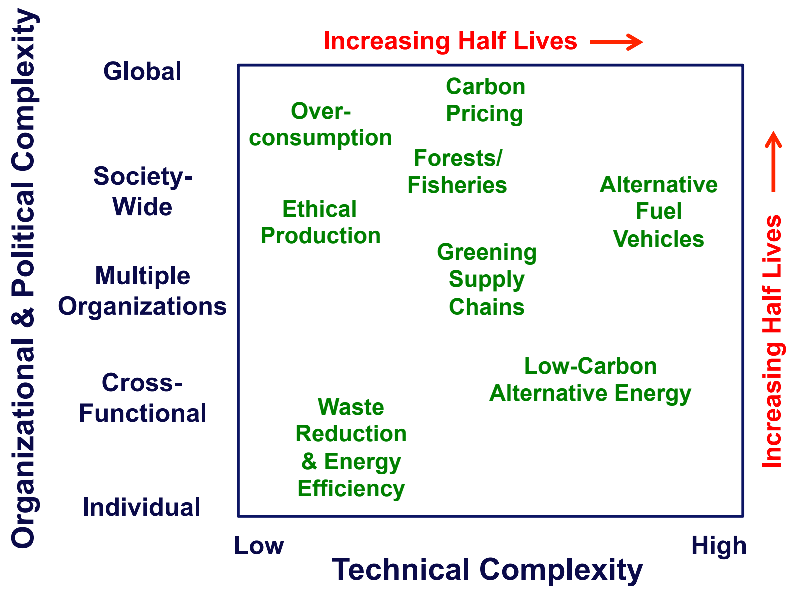


Figure 3. Process improvement half-lives depend on the technical and organizational/political complexity of the process. The complexity of illustrative sustainability issues is shown.

The implications for sustainability are clear. Within firms, we can expect that technically and organizationally simple actions, primarily around resource efficiency and waste generation, will yield large returns and rapid improvement, while programs to improve ethical production, labor standards, and the health, safety and environmental sustainability of the supply chain will prove to be more difficult. Walmart provides a typical example: energy efficiency and waste reduction initiatives, where improvement half-lives are short, were notably successful. More complex supply chain initiatives had mixed outcomes, including some failures (organic cotton, sustainable seafood, RoHS-compliant electronics sourcing, e-waste take-backs), while Walmart chose not to address organizationally and politically complex issues such as ethical sourcing and working conditions,[9] and reportedly "played the lead role in blocking an effort to have global retailers pay more for apparel to help Bangladesh factories improve their electrical and fire safety," with fatal consequences for those who labored on its behalf.[10]

Improvement half-lives are not constant over time. Over time, improvement rates slow as performance approaches physical limits. Typically, as the easy improvements are made, the technical and organizational complexity of the next improvement effort increases, shown in Figure 2 as the balancing *Low Hanging Fruit* feedback, B2. Although the best fit to the US auto fatality data for the entire period from 1910 to 2010 yields an average improvement half-life of about 21 years, the estimated improvement half-life for the decade from 1910-1920 is just 12 years, while the best fit for the period 1990-2010 yields a half-life of 29 years. Safety-related innovations at the dawn of the auto age included such low hanging fruit as brakes, headlights and taillights, windshields and windshield wipers, stop signs and traffic laws. Recent innovations—air bags, antilock brakes, traction control, stronger social norms against drunk driving—involved far greater technical and especially organizational, political and social complexity.

The rate of problem introduction is also at least partly endogenous. As the stock of process problems falls and the organization's products and processes improve, quality and functionality rise while costs fall. Better, less expensive products attract new customers and find new uses, creating new process problems. The balancing *Rebound Effects* feedbacks (B3 in Figure 2) undermine the benefits of improvement activity by introducing new process problems as a consequence of improvement itself. For example, as automobiles and roads became better, cheaper, and more widely available, driving increased. The growth in VMT per capita, together with population growth, caused total US VMT per year to grow explosively, from essentially zero in 1900 to 250 billion in 1945 to nearly 3 trillion in 2010, an increase of nearly a factor of 12 from 1945 to 2010. Further, as autos became safer, people drove faster and in more dangerous conditions, slowing the improvement in fatalities per VMT, an example of a rebound effect through risk homeostasis.[11] As a consequence automobile fatalities in the U.S. grew from 36 in 1900 to nearly 27,000 in 1945, and have exceeded 30,000 per year ever since, despite continued reductions in fatalities per VMT.

Sustainability programs are subject to similar rebound effects: reducing the waste and energy embedded in a product lowers costs and prices, stimulating demand for the more efficient product (the direct rebound effect) and increasing people's disposable income, so that overall consumption rises (the indirect rebound effect).[12] Population growth, rising incomes and consumption per capita and rebound effects can overwhelm even large improvements in ecoefficiency.

The implications for sustainability are clear: goals to reduce resource use and waste generation must be framed in absolute terms. For example, limiting global warming to the internationally ratified goal of no more than 2°C above preindustrial levels requires global CO_2 emissions to fall roughly 80% relative to 2005 by 2050. However, many firms and nations pledge only to reduce their CO_2 *intensity*, measured in CO_2 generated per unit produced or per dollar of revenue, because they expect and desire to grow. Thus, in 2009 China pledged to reduce the carbon intensity of its economy—CO_2 per unit of real gross domestic product—45% by 2020 relative to the year 2005. However, even if China's economy grew at a conservative rate of only 7%/year, its real GDP would grow over those 15 years by a factor of 2.9. Even if China achieves its intensity goal, its CO_2 emissions would rise by 57%. In fact, China's emissions have grown dramatically. Now the world's largest emitter, China generated more than 26% of world CO_2 emissions from fossil fuels in 2011.[13] Nature does not care about the CO_2 intensity of your factories or the concentration of carcinogens in your effluent stream. Total emissions accumulate in the atmosphere and total carcinogen emissions determine the risk borne by your workers, your neighbors and yourself.

The Capability Trap

The model above suggests why improvement rates vary across industries and processes. However, in many situations improvement and learning are not taking place even at the potential rate. Numerous studies demonstrate that individuals and organizations have not taken advantage of opportunities to reduce their energy use and waste generation even when these have positive net present value, high ROI and short payback times, and involve ready-to-use, off-the-shelf technology. As Amory Lovins puts it, "the low-hanging fruit is mushing up around our ankles and spilling in over the tops of our waders while the innovation tree pelts our head with more fruit."[14] McKinsey,[15] for example, finds more than 12 $GtCO_2e$/year of greenhouse gas emissions—nearly a third of the global total in 2012—can be abated at negative cost using well-established technologies. While the existence of such win-win opportunities may seem like good news, it is actually a sign that the improvement process is failing: Something has gone badly wrong when profitable opportunities to eliminate defects, cut energy use and waste, and improve sustainability go unimplemented.

Why are profitable improvement opportunities so often left on the table? Some economists argue that win-win investments must not exist because rational actors would have already made them, therefore studies reporting such opportunities either ignore other costs or inflate the benefits. Others acknowledge the existence of win-win investments and instead attribute underinvestment to market failures. Actors may lack access to the credit necessary to finance up-front investments. Information asymmetries and principal-agent problems such as the famous landlord-tenant problem may arise when actors making investments do not directly realize savings, or when sellers of a technology cannot credibly communicate future (unobservable) benefits.[16]

Other scholars stress the role of behavioral and organizational biases. Thus people tend to evaluate projects from the parochial perspective of their organizational function rather than what's best for the organization as a whole, buy products with lower initial costs despite higher life-cycle costs, and resolve to go to the gym and start a diet….tomorrow. And organizations often face market and stakeholder pressures to prioritize short-term results over longer-term investment.[17]

Certainly, the costs of some improvement opportunities are underestimated, and principal-agent problems, information asymmetries, management biases and short-termism affect investment decisions in organizations. These phenomena don't merely afflict environmental, health, safety and other pro-social improvement opportunities. Many, perhaps most, improvement programs fail. From airline kitchens to health care, similar firms in the same industry, units within the same firm, and even different floors of the same hospital exhibit persistent performance differences despite powerful financial incentives for improvement, market forces favoring high performers, and the wide availability of process improvement methods that should lead to widespread adoption of best practices.[18] For example, total factor productivity varies by about a factor of 2 between the 10th and 90th percentile firms in the same 4-digit SIC industries in the US, and by more than a factor of 5 in China and India.[19]

One common failure mode for process improvement is the *capability trap*.[20] Figure 4 augments the core structure of defect reduction with the feedback processes affecting the intensity and effectiveness of improvement activity. Managers responsible for any process, whether production, product development, maintenance, human resources, or environmental performance, are responsible for the performance of that process against target or required performance. When performance falls short of the target, managers have two basic options to close the performance gap: working harder or working smarter. Working harder includes adding resources (hiring, capacity expansion), increasing work intensity of existing resources (overtime, shorter breaks), and boosting output per person-hour by cutting corners (skipping steps, cutting testing, foregoing maintenance, failing to follow safety procedures). These activities form the balancing (negative) Work Harder feedback, B4: the performance gap leads to greater effort, longer hours, corner cutting, deferring maintenance, and other shortcuts that improve performance, thus helping to close the gap. Alternatively, managers can interpret the performance gap as a sign that the organization's capabilities are insufficient. They can seek to increase improvement activity designed to eliminate the root causes of poor performance, including improving the productivity and reliability of plant and equipment, and investing in the capabilities that make improvement effort effective, including improvements in physical equipment and in human capital that build people's skills and knowledge of best practices, enhance adherence to those practices, and build cooperation and trust. Investing in capability improvement forms the balancing Work Smarter feedback, B5.

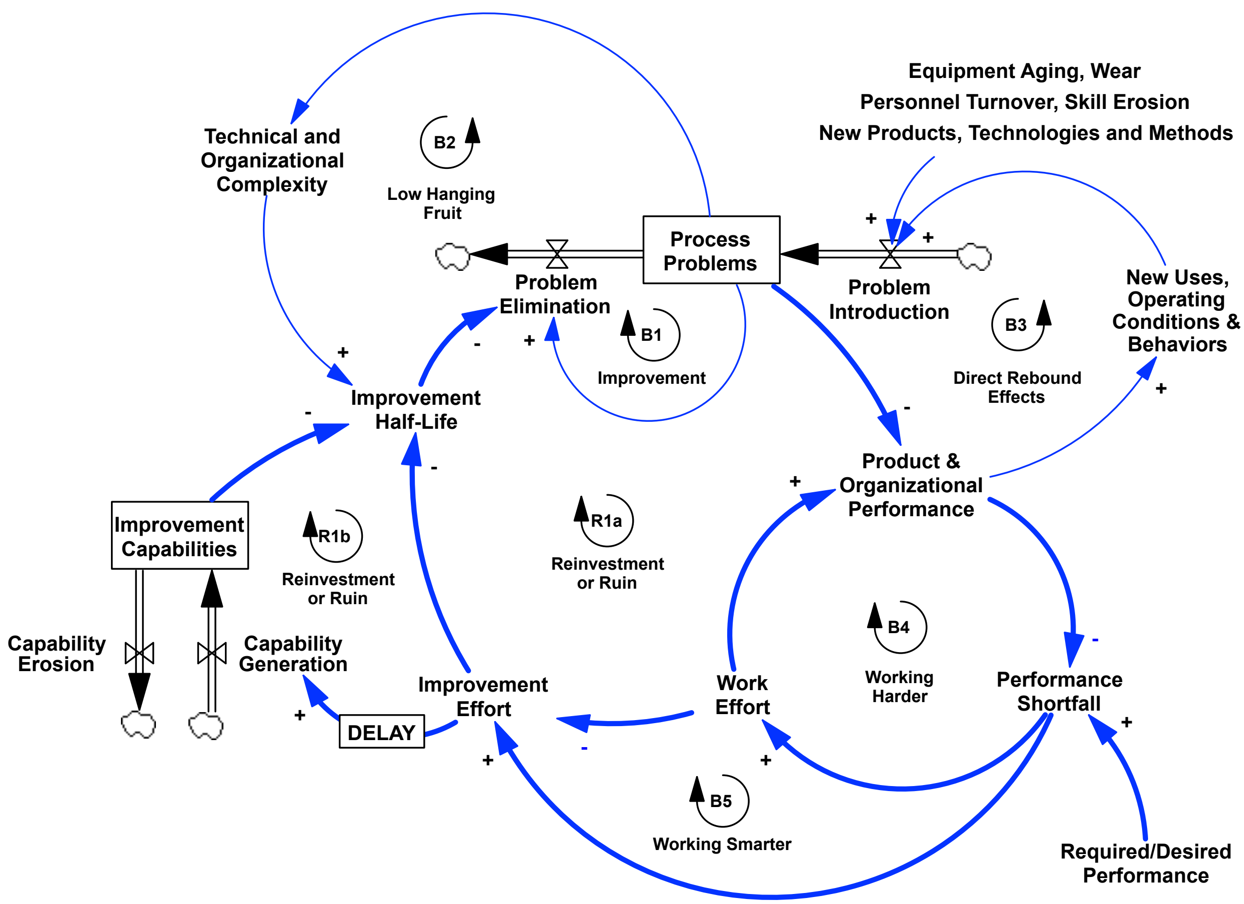


Figure 4. The capability trap: Structure

Improvement half-lives therefore depend not only on the technical and organizational complexity of the process, but on the intensity and effectiveness of improvement effort.[21] The greater the effort devoted to improvement, and the greater the organization's improvement capabilities, the shorter the improvement half-life.

The organization's capabilities are shown as a stock: capabilities, from productive, well-maintained equipment to skilled workers to knowledge of improvement methodologies to trust between workers and management and across organizational boundaries, are assets that build up as the result of investment and erode over time through as equipment ages, employees leave, and by changes in the environment that render existing skills, knowledge and relationships obsolete.

Working harder and working smarter interact because time is limited. When organizations are heavily loaded, increasing work effort comes at the expense of improvement, maintenance, learning, training and other activities needed to preserve and enhance capabilities, as illustrated by the following comment of a manager in an electronics assembly plant:

> "...supervisors never had time to make improvements or do preventative maintenance on their lines...they had to spend all their time just trying to keep the line going, but this meant it was always in a state of flux, which in turn, caused them to want to hold lots of protective inventory, because everything was so unpredictable. A quality problem might not be discovered until we had produced a pile of defective parts. This of course meant we didn't have time to figure out why the problem happened in the first place, since we were now really behind our production schedule. It was a kind of snowball effect that just kept getting worse."[22]

The result is the reinforcing feedbacks denoted "Reinvestment or Ruin" (R1a and R1b). As the name suggests, these feedbacks can operate either as virtuous cycles that cumulatively build capabilities and performance, or as vicious cycles that degrade both. An organization that increases the time and resources devoted to improvement will, after a lag, augment its capabilities and performance, easing the performance gap and yielding still more time and resources for further improvement in a virtuous cycle. In contrast, if managers respond to a performance gap by increasing pressure to boost output, the time spent on improvement falls, and the organization's improvement capabilities erode. Eventually, problem elimination falls below the rate at which new problems are introduced by changes in products, processes, personnel and other conditions, increasing the throughput gap further and forcing ever-greater reliance on working harder. The vicious cycle quickly drives out any meaningful improvement activity, leading to low capabilities and poor performance, and, all too often, to major accidents, environmental harms or organizational failure.

Many believe that an organization would never allow itself to fall into the capability trap: after all, doesn't everyone know that "an ounce of prevention is worth a pound of cure" and that "a stitch in time saves nine"? Since the quality revolution of the 1980s, businesses claim to understand that it is better to eliminate the root causes of defects than to fix defects later on. Consider, however, an organization facing a performance gap. Working harder is the fastest way to close the gap. Overtime, deferring maintenance and cutting corners will quickly boost output. The results are highly observable, closely related in time and space, and quite certain: managers can be highly confident that a 10% increase in work hours will yield about 10% more throughput. However, there is a long lag between an increase in the time spent on improvement and the resulting increase in capabilities, and both the length of the lag and the yield to improvement effort are uncertain. Improvement experiments often fail; search takes time and may lead down some blind alleys. It takes time to develop the capabilities that make improvement effort productive, to train people in improvement, develop norms that prevent corner cutting, and build new routines, networks of relationships, commitment and trust. These features interact to bias many organizations towards working harder instead of working smarter even when the payoff to working smarter is higher.

Figure 5 illustrates using the example of maintenance in a manufacturing plant.[23] Initially, the plant is performing well, with high uptime, equipment reliability, product quality and safety. The bulk of total spending on maintenance is devoted to proactive maintenance and improvement. Now imagine a company-wide budget cut (due to recession, competitive pressures, or other causes). The maintenance manager must cut expenses. Reactive maintenance cannot be cut: when equipment fails it must be fixed, lest plant uptime falls and customer commitments cannot be met. Instead, proactive maintenance and improvement suffer, along with training, part quality, design improvement efforts, and, all too often, adherence to safety protocols. The first impact? Maintenance costs fall, closing the budget gap, and plant uptime rises, because operable equipment is no longer taken down for preventive/scheduled maintenance. Soon, however, the stock of latent defects starts to rise because the rate at which maintenance and process improvement eliminate defects falls below the rate at which aging and wear introduce new ones. The rate of breakdowns and failures grows, increasing the reactive maintenance workload and costs, further lowering proactive maintenance and improvement.

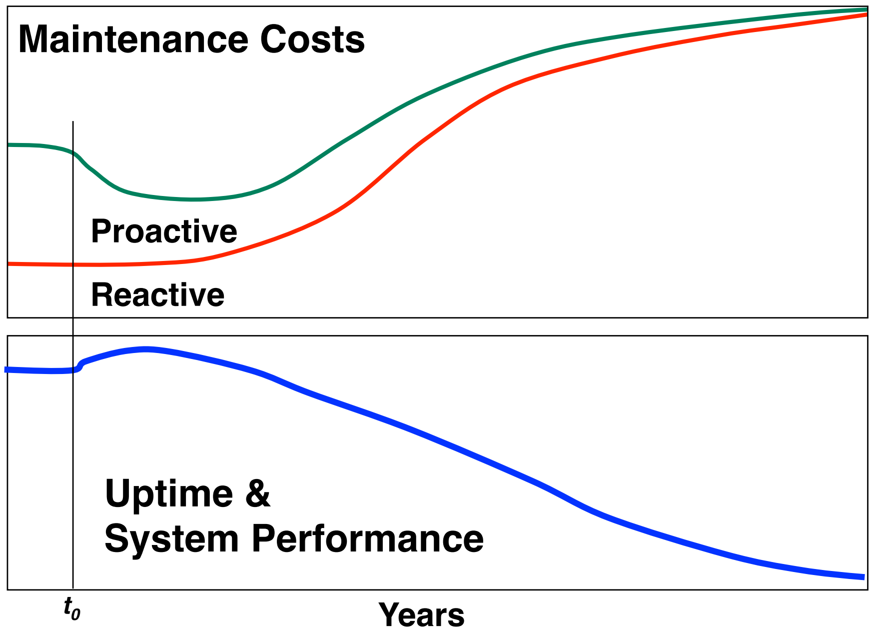


Figure 5. The Capability Trap: Dynamics. Budget cuts at time t_0 force the organization to cut proactive maintenance and improvement activity. As organizational capabilities gradually fall, defects increase, increasing reactive maintenance and forcing further reductions in proactive maintenance and process improvement. The self-reinforcing Reinvestment or Ruin feedbacks R1a and R1b in Figure 4 operate as vicious cycles to drive the organization in to a state of low safety and reliability, poor performance, and high costs.

As rising breakdowns cut plant uptime and output, revenue falls and budgets are cut further. Squeezed between growing expenses and falling budgets, managers feel compelled to cut proactive maintenance and process improvement effort still further. The plant becomes trapped in a vicious cycle of increased breakdowns, higher costs for urgent repairs, lower uptime, greater production pressure, less improvement effort and still more breakdowns and higher costs.

Soon, the organization finds itself in a paradox: it pays more to maintain its plants than the industry average, yet gets less for it. Risks to the health and safety of employees and the community rise as the equipment deteriorates and production pressure leads to corner cutting.

The consequences are often tragic. Recent examples just from the United States include the

2005 BP Texas City refinery explosion (15 dead), the 2007 collapse of the I-35 bridge in Minneapolis-St. Paul (13 dead), the 2008 Imperial Sugar explosion (14 dead), the 2009 Massey Energy Upper Big Branch coal mine explosion (29 dead), and the 2010 Deepwater Horizon explosions and oil spill (11 dead). All resulted from capability trap dynamics, including inadequate inspections, maintenance and improvement activity, excessive cost and production pressure, and corner cutting. For example, the Chemical Safety Board's report on Imperial Sugar found:

> "Imperial Sugar and the granulated sugar refining and packaging industry have been aware of sugar dust explosion hazards as far back as 1925….However, plant] equipment was not designed or maintained to minimize the release of sugar and sugar dust into the work area….Emergency evacuation plans were inadequate and the company did not conduct emergency evacuation drills….The secondary dust explosions would have been highly unlikely had Imperial Sugar performed routine maintenance on sugar conveying and packaging equipment….[The] resulting fatalities would likely not have occurred if Imperial Sugar had enforced routine housekeeping policies and procedures…."[24]

The power of management pressure to work harder at the expense of improvement, maintenance and safety is illustrated by a 2005 memo sent to all Massey Energy employees by then-CEO, Donald Blankenship:[25]

> "If any of you have been asked by your group presidents, your supervisors, engineers or anyone else to do anything other than run coal (i.e. build overcasts, do construction jobs, or whatever) you need to ignore them and run coal….This memo is necessary only because we seem not to understand that the coal pays the bills."

The US Mine Safety and Health Administration report on the Upper Big Branch mine calamity documented the impact of that pressure, including failure to identify, report and correct "obvious hazards", "inadequate training" and a "culture of intimidation," as illustrated by a miner's testimony:

> "...they (miners) were scared if they took the time to ventilate that way it should be…they'd be fire [sic] or gotten rid of…you knew that you better go ahead and mine the coal or --- the atmosphere around Massey was, you know, you just keep your mouth shut and do it if you want to keep your job."[26]

If financial and production pressures cause managers and employees to violate federal law and cut corners in ways that obviously threaten their own lives, how often does more subtle pressure to serve customers or get the new product to market prevent people from working on improvement and sustainability initiatives, initiatives that they often view as peripheral to their jobs?

Now consider what happens when an organization seeks to escape the capability trap. Figure 6 shows the plant illustrated in figure 5, now stuck in the trap, with high costs and low uptime, reliability, safety and quality. At time t_1, the managers initiate an improvement program, focusing on proactive maintenance and improvement. The first impact? Costs rise while uptime and output fall.

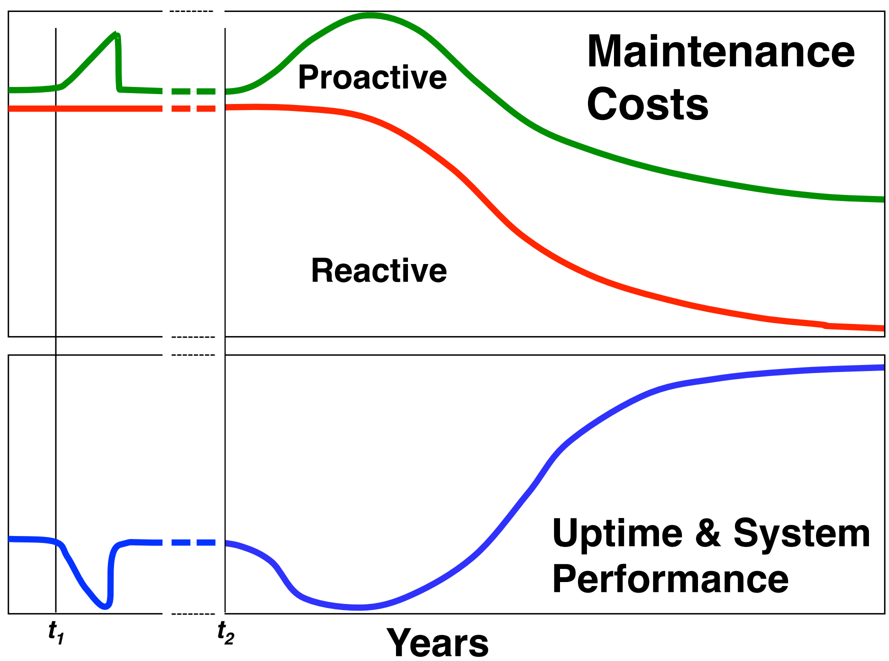


Figure 6. Escaping the Capability Trap: Worse-Before-Better. Improvement effort is given priority at time t_1, but the increase in costs and drop in uptime causes the organization to abandon the effort. If a new effort begins (at time t_2) and is not abandoned, then the initial cost increase and performance drop eventually reverse, leading to lower costs and higher uptime, output, quality, reliability and safety, in a worse-before-better pattern.

Costs rise, of course, because the maintenance group must increase the level of preventive maintenance and improvement activity, while still carrying our reactive repair work at the same rate. Uptime and production fall because operable equipment must be taken off line to perform preventive maintenance and test improvement ideas. In many organizations, the next impact is the abandonment of the improvement initiative.

What happens, however, if the organization doesn't give up when costs rise and uptime falls? After a new improvement program is started (at time t_2 in the figure) the increased improvement effort and gradual growth in improvement capabilities eventually begin to eliminate process problems faster than new ones are introduced. Failures start to fall, uptime and output rise, and the burden of reactive maintenance eases, allowing resources to be reinvested in still more proactive maintenance and improvement, speeding defect reduction: the Reinvestment or Ruin feedbacks now operate as virtuous cycles, bootstrapping the plant to low costs and high performance. Note, however, that the system exhibits Worse-Before-Better (WBB) behavior.

Once an organization has fallen into the capability trap, worse-before-better behavior is inevitable: to improve the organization's capabilities and reduce process problems requires either cutting output in the short run by reallocating existing resources from production to improvement, or increasing total costs so that improvement effort can rise while maintaining current output.

The depth and duration of the WBB behavior depends on two factors. First, organizational slack (or, since managers equate the term "slack" with "waste", a "strategic margin of reserve capacity") can decouple the working harder and working smarter processes to some extent. Slack allows an improvement program to be implemented without compromising work effort, limiting the performance drop and surge in production pressure that then quenches improvement effort before capabilities can improve and process problems can be eliminated. Slack can take a variety of forms, from financial reserves used to increase capacity and buffer earnings, to the high ratio of kaizen experts to front-line workers in Toyota plants, to a committed, well-rested workforce willing and able to work overtime when called upon, to excess production capacity or inventories that can be used to maintain shipments when operable equipment is taken off-line for maintenance and improvement or personnel are reallocated from production to improvement.

Second, the shorter the improvement half-life of the process, the shorter and milder the WBB behavior will be. In settings with very low technical and organizational complexity, performance can improve so quickly that the initial decline is negligible. Many energy efficiency, water use and waste reduction programs fall into this category. MIT, for example, had gradually fallen into the capability trap, accumulating a backlog of deferred maintenance of about $2 billion, a largely reactive and overburdened maintenance organization, and high energy, water and other utility costs. As part of a campus-wide improvement program, the maintenance department implemented a continuous commissioning program. The biology building, a relatively new facility built in 1995, was one of the first projects. Defects had crept in to the equipment after years of mostly reactive maintenance. Sensors and controls had drifted so that the building was heating and cooling itself simultaneously.[27]

Eliminating that waste, along with cleaning and repairs to other HVAC system elements, yielded immediate energy savings worth about $360,000 per year. The total cost of the program was about $150,000. The savings were so large and so immediate that there was essentially no WBB behavior.

In contrast, the long improvement half-life for technically and organizationally complex processes means a longer, deeper WBB period after improvement is initiated, and often thwarts successful implementation, or leads to unanticipated harms as different functions improve at different rates. For example, long-improvement half-lives for product development compared to manufacturing caused excess capacity and other unintended impacts of successful quality improvement at semiconductor firm Analog Devices, leading to a large drop in profits, the first layoffs in the history of the firm, and the collapse of the firm's quality improvement effort.[28]

The short- and long-run impacts of policies are often different[29] and manifest in many familiar settings: overtime boosts productivity today but leads to lower productivity, higher errors, and increased worker turnover later; credit card debt boosts consumption today but forces austerity when the bills come due. But WBB is particularly problematic in sustainability contexts because of the long time delays compared to many business processes. Restoring a depleted fishery requires cutting the catch long enough for stocks to recover; doing so may idle the fleet longer than the fishing community can survive. Converting a farm from conventional to organic production may increase costs and reduce output for several years until organic practices can restore the communities of bacteria, insects, and other organisms that rebuild soil fertility and provide natural protection from pests. Even longer lags arise in the response of the ozone hole to CFC production, the accumulation of long-lived toxins in the food chain and in our bodies, and in the response of the climate to changes in GHG emissions.

The implications for sustainability programs are clear.

First, few organizations today have much slack. Decades of downsizing, rightsizing, outsourcing, and cost reduction have increased the workload on front-line workers and managers alike. Many organizations are stuck in capability traps involving basic functions such as maintenance, customer satisfaction, and product development, and survive through continual firefighting.

Second, sustainability initiatives add to the existing workload on already-overloaded personnel. Many opportunities with high NPV and short payback times go unimplemented because the organizations lack the staff and budget to act on them, and the constant pressure to control costs means managers are often unwilling to add those resources even if the payoff is high. Most organizations view maintenance and operations as cost centers to be minimized, not profit centers.

Third, high work pressure, intense competition and pressure from financial markets mean initial improvements are often harvested through cost cutting, weakening the reinvestment feedbacks so essential in building the capabilities and resources for continuous improvement.

Fourth, sustainability initiatives involving technically and organizationally complex processes are particularly vulnerable to the capability trap because they involve longer, deeper periods in which performance falls and/or costs rise before the benefits of improvement will manifest.

Fifth, the capabilities needed to address complex sustainability challenges will not develop if organizations believe that they cannot sustain the investments needed to succeed. A history of failed efforts can lead to a vicious cycle of eroding goals and low ambition seen today in widespread cynicism about the prospects to mitigate GHG emissions.[30]

Forward-thinking organizations address all of these barriers to escape the capability trap. They frame the resources needed to get started as investments, not expenditures. They use life-cycle costs instead of up-front costs to assess the return to proposed initiatives. They forge agreements with senior management to reinvest at least a portion of those savings in further improvement. They use the improvement half-life framework to gauge the complexity of their projects and set realistic goals for progress. They use the savings from initial programs with low hanging fruit to begin work on the programs that may be more difficult and take longer but offer larger potential benefits. They build shared understanding of improvement dynamics, including worse-before-better, through training and interactive simulations. They reduce the bias toward working harder by changing incentives for all, from senior executives to front-line employees, to reward improvement and investments in capabilities. They are willing to fire those who cut corners, compromise safety, or otherwise undermine capabilities even if those employees or managers deliver high throughput and profits. Table 1 lists a few examples.

- Many organizations have established "revolving green loan funds" to finance sustainability programs, using the returns on those investments to finance still more improvement.[31]
- The facilities manager in a university without a green loan fund was denied the budget to implement energy retrofits despite their high expected return. He went to the manager responsible for the fuel budget and "borrowed" the funds needed to implement the program. The energy savings "repaid" the "loan"—and then some—so quickly there was no negative impact on the fuel manager's budget.
- Many firms use "hackathons" in which employees can work on any projects they like to generate creative ideas for new products and processes, including sustainability programs.
- A product line manager in a corporation developed metrics to assess savings from improvement, then agreed to take the risk of funding the program in return for an agreement with senior management allowing the product group to retain most of the savings for further improvement.
- The sustainability manager for a major firm in the life sciences won approval to hire more staff by arguing that the savings generated would more than pay for the costs. In the first year alone, the new hires generated more than twice their fully-loaded costs in documented savings.
- The product engineering group of a major manufacturer was told by senior management to cut warranty costs 50% in three years. Working backwards, they determined that hitting that target given the product development cycle time required an improvement half-life of 6 months, far shorter than evidence suggested was possible. They used the improvement half-life framework to set more realistic goals, leading to higher morale, lower turnover, and faster progress.
- A large firm was using a rule of thumb requiring energy retrofit projects to yield payback times of two years or less, implying a simple ROI of 50%/year or higher. Managers argued that the hurdle rate for such investments should be the same as the much lower rate used for other capital budgeting decisions (or lower, given the lower risks of the retrofit projects).
- In partnership with the World Wildlife Fund, dozens of firms, including IBM, Johnson and Johnson, Sony, Sprint and Volvo, have set goals for absolute reductions in their greenhouse gas emissions and other forms of waste, not goals for reductions in emissions per dollar of sales. The short half-lives for energy efficiency and waste reduction have led to large emissions reductions and significant financial savings.[32]
- Major firms in the chemical and oil industries, among others, use interactive role-play simulations and training in systems thinking to build shared understanding of the dynamics of maintenance and improvement, including how to manage the worse-before-better dynamic, generating billions in savings while improving safety and environmental quality.
- Managers at a major software developer are accountable not only for delivering projects on time and within budget but for adhering to the firm's development process. Those who cut corners can and have been fired even if they bring their projects in on time and under budget. Senior leadership believes corner cutting initiates the slippery slope of the capability trap and that tolerating it would send a toxic message to all employees that corner cutting—and covering it up—is how to get ahead. By firing those who, as GE's Jack Welch put it, fail to "live the values" of the organization, no matter how large their apparent contribution to the bottom line, senior management not only encourages people to do the right thing but builds a high-capability organization filled with those motivated by a worthy mission, not short term gain.

Table 1. Creative organizations find ways to set appropriate goals, kick-start improvement, reinvest savings and overcome the capability trap, for both normal operations and programs in sustainability.

Radical Disruption: building new, sustainable industries

For the reasons articulated above, ecoefficiency, waste reduction and other improvements to existing processes in existing organizations, although necessary in reducing the global ecological footprint of humanity down to a sustainable level, are not sufficient. Many pin their hopes on the creation of entirely new industries, built by new firms with intrinsically sustainable operations and producing sustainable products. Solar, wind and renewable energy sources will displace fossil fuels. Vehicles powered by renewable, low-carbon energy will displace internal combustion vehicles powered by fossil fuels. Organic, local, small-scale agriculture will displace monocultures and factory farms.

The history of such transitions is one of path dependence, false starts and delays. Consider the transition to alternative fuel vehicles. There is no doubt that the current dominant design, internal combustion engine (ICE) vehicles powered by fossil fuels, cannot scale with current technology and patterns of use. If everyone drove the way those in the US do today, then in 2050 the projected population of 9.3 Billion people would be driving 7.8 billion passenger vehicles, consuming 382 million barrels of oil per day, (more than 5 times total world production today), emitting 60 billion tons of CO_2 per year (almost double total world emissions today), and taking up 143,000 sq. kilometers, an area the size of Bangladesh, just in parking spaces.[33]

A wide range of alternative drive train and fuel technologies are now contending to be the new dominant design, including electric, hydrogen fuel cells, internal combustion engines powered by hydrogen, ethanol, methanol, biofuel blends such as E85, compressed natural gas (CNG), or combinations thereof, including conventional and plug-in hybrids. The history of attempts to introduce alternative fuel vehicles can be characterized as "Sizzle and Fizzle" (Figure 7). Multiple attempts to (re)introduce electric vehicles have failed. Brazil's first attempt at an ethanol powered fleet failed, and initially promising programs to introduce natural gas vehicles stagnated in Italy and withered in Canada and New Zealand after initial subsidies ended.[34]

The failure of AFV programs to date is commonly attributed to high costs and immature technology. Certainly the high cost and low functionality of AFVs compared to fossil-ICE limits their market potential today, particularly in nations like the US where gasoline is priced far below the level that would reflect its environmental, climate, health and other externalities. More subtly, the current low functionality and high cost of alternatives, and low gasoline taxes, are endogenous consequences of the dominance of the internal combustion engine and the petroleum industry, transport networks, settlement patterns, technologies, and institutions with which it has coevolved. The dominance of internal combustion suppresses the emergence of alternatives, maintaining the dominance of fossil-ICE. These feedbacks mean that sustained AFV adoption would be difficult even if AFV performance equaled that of fossil-ICE today.[35]

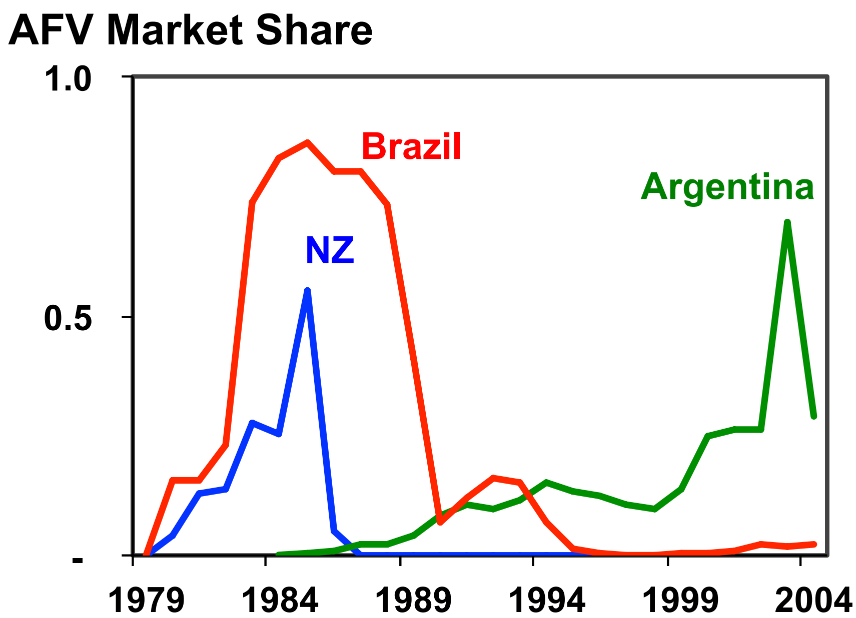


Figure 7. Sizzle and fizzle behavior in the adoption of alternative fuel vehicles (AFVs): Brazil (ethanol); New Zealand and Argentina (CNG).

The enormous scale of the automobile industry and associated infrastructure creates a set of powerful positive feedback processes that confer substantial advantage to the incumbent fossil-ICE technology (Figure 8). First, AFVs including electrics, hydrogen, CNG and biofuels require new fueling infrastructure incompatible with the existing fuel supply chain and retail distribution network. Drivers will not buy AFVs without ready access to fuel, parts, and repair services, but energy producers, automakers and governments will not invest in AFV technology and infrastructure without the prospect of a large market—the so-called chicken and egg problem, shown in the figure as the *Infrastructure* loop. Fuel availability also affects VMT per year for those early adopters who buy AFVs: without ubiquitous fueling infrastructure, early adopters will drive fewer miles and avoid areas in which fueling infrastructure is sparse, limiting AFV fuel demand and therefore the profitability and deployment of fueling infrastructure in those areas, further suppressing the use of the few AFVs that are purchased. AFV drivers, knowing that fuel is not readily available, will likely seek to maintain a large buffer, leading to topping off behavior that reduces the effective range of the AFVs even further below the range of fossil-ICE vehicles, and may lead to congestion at the few fuel stations that are deployed. These behavioral effects cut both AFV miles driven and the attractiveness of AFVs to potential customers, suppressing the growth of the market (the *Range Anxiety* feedback).

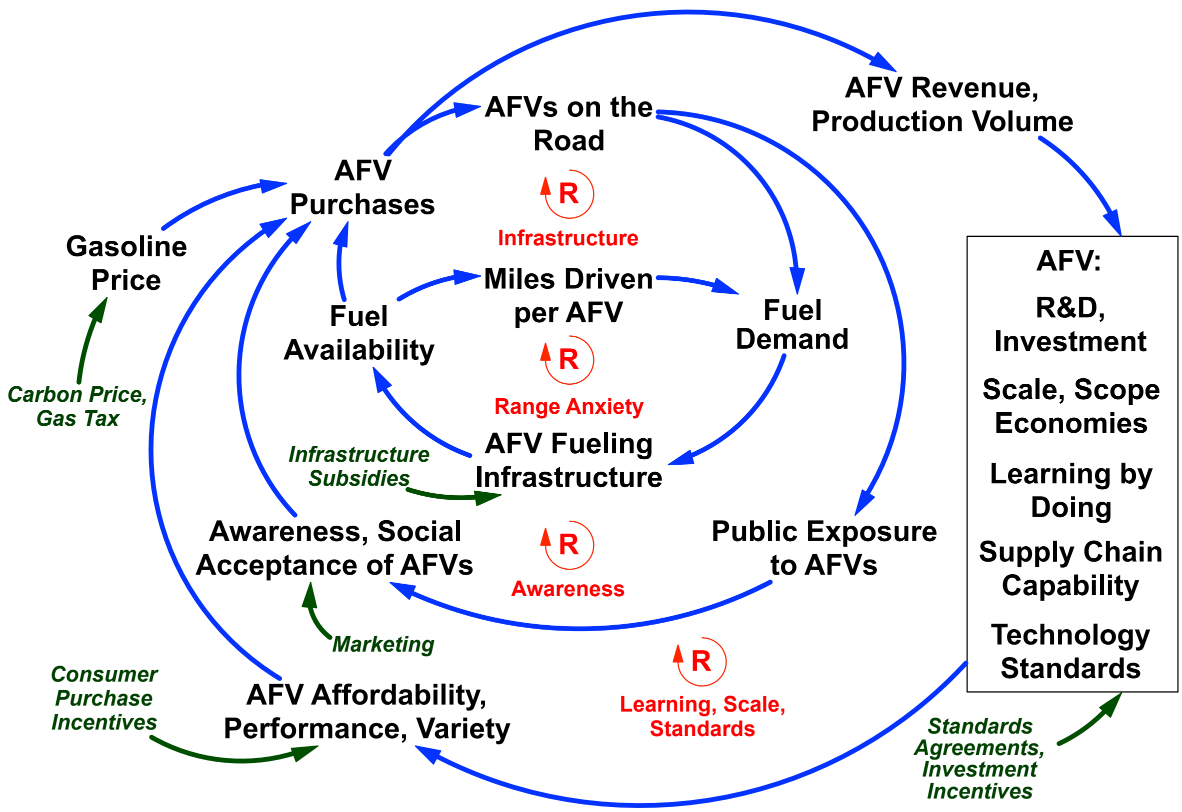


Figure 8. Reinforcing feedbacks conditioning the adoption of Alternative Fuel Vehicles (AFVs).

Demand for AFVs is significantly conditioned by word of mouth, social exposure to the vehicles, and other social processes. Keith[36] found that adoption of the Toyota Prius powerfully driven by the installed base in a potential buyer's local region, with marketing far less effective. People need to become familiar with a new type of vehicle through multiple exposures, word of mouth, and other social network effects before they are willing to put it in their consideration set. Thus low initial awareness suppresses purchases, which limits the number of AFVs on the road and thus public exposure to and word of mouth about the AFV, further suppressing purchases (the *Awareness* loop).

Even if potential customers were sufficiently familiar with AFVs to consider purchasing them, the utility of such vehicles is initially low because the current state of technology for many alternative drive trains means these vehicles are more expensive, offer lower performance, range, cabin and storage space, and are available in fewer makes and models than fossil ICE vehicles. The lack of standards, both across and within AFV platforms, suppresses demand as consumers delay purchases until they are sure that a particular platform will survive. For example, current battles over charging formats and plug shapes for electrics, such as SAE 1772 vs. CHADeMO, confuse consumers and raise the costs and uncertainties facing infrastructure providers. Improvements in costs, performance, range, interior space, variety, and the emergence of standards are driven by scale economies, R&D, learning by doing and field experience, but these, in turn, are suppressed by low initial sales of any one AFV platform (the *Learning, Scale, and Standards* loops).

Figure 8 also shows the principal policy levers available to industry actors and governments to stimulate the AFV market, including subsidies offered to consumers by either governments (tax credits, access to HOV lanes) or auto OEMs (prices below unit costs), subsidies to infrastructure providers or government installed fuel points, marketing (paid by either the industry or governments), and carbon prices or higher gasoline taxes . However, the network of reinforcing feedbacks above, and the dominant position of the fossil-ICE platform—full familiarity and acceptance, ubiquitous fueling, part, and repair infrastructure, a full range of makes and models, low costs and high performance—mean any AFV faces a long uphill battle before it achieves the installed base, awareness, scale and standardization to succeed. Simulations capturing the feedbacks above show that crossing the tipping point to sustained success requires the early adoption of standards and much larger and longer marketing campaigns and subsidies for vehicles and infrastructure than is typical in most markets. Failure to provide such sustained, coordinated support leads to the sizzle and fizzle behavior observed in many markets.[37]

In terms of the improvement half-life framework, the AFV industry faces not only high technical complexity, but high organizational and political complexity: success will require coordination across auto OEMs, infrastructure providers, the energy supply chain, local, state and federal governments, and other actors. At the moment such coordination is weak.

Consumers can choose among conventional hybrid electrics, plug-in hybrids, pure battery electrics, clean diesel, E85, flex-fuel, CNG and hydrogen powered vehicles, and leading OEMs including GM and Ford are pursuing an "all of the above" strategy by promoting portfolios of different AFVs. But hedging bets due to the uncertainty over which technology will become the new dominant design limits the ability of any AFV to achieve the scale needed to succeed, increasing uncertainty and delaying the transition away from fossil-ICE that is so urgently needed.

Although the specifics will vary, similar reinforcing feedbacks exist around other core infrastructures of modern society, including agriculture, air transportation, public transit, the electric grid, and settlement patterns. All must be transformed away from their current unsustainable structures to new, low-carbon and low waste, sustainable systems. All face high tipping thresholds. Success will require overcoming the market failures created by these dynamics. Coordination is required among actors in these industries including suppliers, complementors, consumers and government. Achieving such coordination can be difficult. Yet organizations and governments have successfully coordinated to establish thousands of standards, overcome market failures and preserve common pool resources in diverse settings, through both industry self-regulation and government regulation, from local laws to international agreements (Table 2).

Elinor Ostrom, who identified many such successes, articulated key principles for effective management of common pool resources such as fisheries, forests, fresh water, and the climate, and other settings where coordination is required to overcome market failures, such as provision of policy and fire protection for communities. These principles include rules adapted to local conditions, inclusion of key parties in decision making, effective and independent monitoring, graduated sanctions to punish those who violate community rules, accessible, transparent conflict resolution processes, self-determination of communities respected by higher-level authorities, and, particularly for large-scale common-pool resources, multiple, nested organizations and management processes (so-called polycentric governance).[38] These principles will also be needed to overcome many of the market failures that currently thwart or delay the development and deployment of the radical innovations needed to promote sustainability.

- Philips and Sony independently developed optical disc storage technology, then worked together to agree on standards for the discs and data storage protocols for them. The resulting open standards led to success of the compact disc for audio recordings and data storage, with hundreds of billions sold. The success of the open standards for CDs stands in stark contrast to format wars over videocassette standards (Sony Betamax vs. Matshushita VHS) and high-definition DVDs (Sony Blu-Ray vs. Toshiba HD-DVD). Importantly, although Blu-Ray ultimately prevailed, the delay created by the format war delayed the development of the market, which ultimately failed as consumers increasingly turned to digital downloads rather than purchasing physical discs.
- The TCP/IP standard, arising out of US Government support through DARPA, became the standard for data transmission in computer networks, enabling the growth of the Internet.
- Industry groups have established thousands of standards, from USB to shipping containers to radio spectrum allocations.
- Since 1947 the ISO (International Organization for Standardization, ISO.org) has worked to create standards to certify process improvement and product integrity in areas including quality management, environment, food safety, energy, greenhouse gases, social responsibility and others relevant to sustainability.
- The Marine Stewardship Council, Forest Stewardship Council and similar multi-stakeholder NGOs work to certify resources are harvested responsibly and managed sustainably.
- Dozens of NGOs and industry groups certify whether foods and other products adhere to "Fair Trade" principles including prices and wages, working conditions, worker rights, and environmental sustainability.
- The UN Convention on the Law of the Sea and International Whaling Commission regulate and set standards for the use of marine resources.
- The 1987 Montreal Protocol provided coordinated standards for the phase out chloroflourocarbons and related compounds that catalyze the destruction of stratospheric ozone. The treaty, amended multiple times to capture evolving science, has been ratified by nearly all nations on Earth and is one of the most successful international agreements to protect a common pool resource. The success of the Montreal Protocol fostered similar negotiations to limit mercury emissions (the Minamata Convention of 2013) and the (so far less-than-successful) climate negotiations under the UN Framework Convention on Climate Change

Table 2. Examples of successful coordination across organizational and political boundaries to manage common-pool resources, set standards, and certify the sustainability of products and processes.

Overconsumption

Suppose, despite the barriers described above, that learning and improvement within incumbent organizations accelerate, and that the coordination and standards required to bootstrap new, sustainable technologies emerge quickly, disrupting and displacing legacy industries. Suppose that rebound effects are mild and that the market failures plaguing common pool resources, from forests to fisheries to water to the climate, are resolved. Would we then be on the road to a sustainable society? Unfortunately the answer is no.

Humanity has already overshot the carrying capacity of the Earth. We are harvesting renewable resources faster than they regenerate, creating pollution and wastes faster than they can be rendered harmless or sequestered, and are overwhelmingly dependent on nonrenewable resources.

Clearly, if innovation is too slow, if capability traps delay or thwart profitable improvements, if market failures prevent the emergence of new, sustainable products and industries, or if technological solutions to the sustainability challenge create harmful side effects, then the result will be overshoot and collapse: technological solutions will be too little, too late or will actually worsen the problem.

More interesting, what happens if the impediments to learning and the creation of new industries discussed above are overcome, if markets work well, if the delays in innovation are short and unintended harms absent? By easing the resource limitations and reducing the environmental degradation that threaten growth, successful improvement and sustainability initiatives enable population and economic output to grow still further. The result: society is once again pushed up against one environmental limit or another. If markets and technology again succeed in addressing those new limits, then human activity grows still further until a new limit and new problems arise.

As long as growth is the driving force there can be no purely technological solution to the challenge of creating a sustainable society. The high leverage points lie elsewhere, in the forces that cause population and economic growth. Even with significant potential for new technical solutions, a prosperous and sustainable future can only be built if growth of both population and material throughput cease voluntarily, before growth is stopped involuntarily by scarcity or environmental degradation.[39] Population growth may end if the demographic transition continues, particularly in the developing world,[40] though the UN population program, despite assuming rapid fertility decline, projects more than 10 billion by 2100. More troubling is the growth in consumption per capita. The world economy has been growing at an average rate of about 3.5%/year (real), a doubling time of only 20 years, and growth is far faster in the emerging economies. Essentially every nation seeks to continue that growth indefinitely. People have strong preferences for growth in their incomes, to earn more than their colleagues and peers, to not only keeping up with, but surpass the Jones'.[41] Since everyone cannot be richer than everyone else, the result is an unwinnable rat race.

Product and process innovation for sustainability, new business models, and other technical solutions are absolutely necessary to create a sustainable economy and society. Business firms have a vital role to play. They must, and many are, improving their processes and products, and developing the new technologies and industries, that are essential in building a sustainable world. The unfolding transition from the unsustainable world of today to a sustainable, prosperous and fulfilling world is, I believe, the greatest entrepreneurial opportunity since the industrial revolution.

But that is not sufficient. Until we learn to end the quest for more—more income, more wealth, more consumption, more than last year, more than our neighbors—then a healthy, prosperous and sustainable society cannot be created no matter how clever our technology, how fast we learn, how quickly we can build new industries. Innovation simply lets us grow until one or another limit to growth becomes binding.

We cannot expect traditional business firms to promote policies that would cause their growth to stop, to cease the marketing and advertising campaigns that urge people to buy ever more, to unilaterally internalize environmental and social costs when their competitors do not. The leverage points for action on overconsumption do not lie within business organizations, but in the beliefs, goals and values of the public, and in public policies that would both enact and reinforce those values. Yet we are not accustomed to asking "how much is enough," uncomfortable connecting abstract debates about growth and scarcity with the way live, with our personal responsibility to one another and to future generations. We don't understand how the quest for more is not only destroying the ecosystems upon which all life, including ours, depend, but is not leading to fulfillment and well-being.[42] Research, teaching and action to promote sustainability must grapple with these issues if we are to fulfill Gandhi's vision of a world in which "there is enough for everyone's need but not for everyone's greed."

Notes

[1] E.g., Running 2012, Rockstrom et al. 2009, and Wackernagel et al. 2002 (updated at http://www.footprintnetwork.org).
[2] The literature is huge. See for example, Argote 2013 and Nagy et al. 2013.
[3] Sterman, Repenning and Kofman 1997 develop and test a system dynamics model of process improvement. See also Argote 2013 and Zangwill and Kantor 1998 for theories of learning and improvement as an iterative cycle.
[4] Schneiderman 1988 developed the concept of the improvement half-life and showed how these vary with technical and organizational complexity. Sterman et al. 1997 showed how differences in improvement half lives in different processes, such as manufacturing and product development, led to stress including layoffs at a major semiconductor firm. Repenning and Sterman 2002 showed how such mismatches undermined improvement programs in a major automaker.
[5] Schneiderman 1988.

[6] See, e.g., Porter and van der Linde 1995, McKinsey 2010, Lovins 2012, Lyneis and Sterman 2013.
[7] Amengual, forthcoming and Locke 2013.
[8] Ostrom 2010.
[9] Plambeck 2010 and Humes 2011 discuss Walmart's sustainability programs.
[10] Greenhouse 2012.
[11] See Wilde 2001 on risk homeostasis.
[12] On rebound effects in energy and sustainability, see Herring and Sorrell 2009 and Sorell et al. 2009.
[13] Carbon Dioxide Information Analysis Center, http://cdiac.ornl.gov/
[14] Lovins is quoted in Olson and Fri 2008, p. 80. On low hanging fruit, see Porter and van der Linde 1995, Lovins 2012 and Lyneis and Sterman 2013.
[15] McKinsey 2010.
[16] See, e.g., Gillingham et al. 2009, Jaffe & Stavins 1994, Howarth & Sanstad 1995.
[17] Bazerman 2009, Yates & Aronson 1983 and Frederick, Loewenstein & O'Donoghue 2002 consider behavioral biases relevant to failures to implement profitable improvement opportunities at the individual and organizational levels. Rahmandad 2012 and Repenning & Henderson 2010 explore the self-reinforcing interactions of organizational short-termism and market pressures.
[18] On failed improvement programs, see Beer et al. 1990, Easton and Jarrell 1998, and Repenning & Sterman 2002. On airline kitchens, see Chew et al. 1990; on medicine, Wennberg 2010. Gibbons and Henderson 2012, 2013 survey the empirical evidence and theory behind PPDs in SSEs.
[19] Syverson 2011.
[20] Repenning and Sterman 2001, 2002 introduce and provide examples of the capability trap; also Keating et al. 1999.
[21] Sterman et al. 1997.
[22] Repenning and Sterman 2002, p. 282-283.
[23] Repenning and Sterman 2001, 2002 and Carroll, Sterman and Marcus 1998 provide detailed examples.
[24] US Chemical Safety and Hazard Investigation Board Report 2008-05-I-GA, http://www.csb.gov/assets/1/19/Imperial_Sugar_Report_Final_updated.pdf.
[25] Fisk, M., Sullivan, B., Freifield, K., http://www.bloomberg.com/news/2010-04-09/massey-s-blankenship-fought-regulators-town-as-coal-mine-operator-s-chief.html. April 9, 2010.
[26] UBB accident report, US Department of Labor, http://www.msha.gov/Fatals/2010/UBB/FTL10c0331noappx.pdf.
[27] Lyneis and Sterman 2013 detail the MIT case, develop a system dynamics model to evaluate policies for improvement, and describe how MIT is implementing these across the campus. Halber 2010 documents the biology building case.
[28] See Sterman et al. 1997, Repenning 2002.
[29] Forrester 1969, Sterman 2000, Repenning and Sterman 2001.
[30] The Climate Interactive Scoreboard (http://climatescoreboard.org) assesses the impact of the commitments individual nations have made under the voluntary Copenhagen Accord of 2009. As of 2013, total commitments, even if fully implemented, are grossly inadequate (see also UNEP 2011). On ambition and aspirations for greenhouse gas mitigation, see http://thinkprogress.org/climate/2013/07/05/2258731/adaptation-or-mitigation-lessons-from-abolition-in-the-battle-over-climate-policy.
[31] E.g., http://www.greenbiz.com/blog/2013/06/07/are-green-revolving-funds-next-frontier-corporate-energy-efficiency
[32] http://wwf.panda.org/what_we_do/how_we_work/businesses/climate/climate_savers/
[33] Projections based on US data for 2008.
[34] On Sizzle and fizzle in alternative vehicles see Hard and Knie 2001, Flynn 2002 and Struben and Sterman 2008.
[35] Struben and Sterman 2008.
[36] Keith 2012.
[37] Struben and Sterman 2008, Keith 2012.
[38] Ostrom 2010.
[39] Sterman 2012, Meadows *et al.* 2004, Daly 1991.
[40] Caldwell 2006.
[41] Sterman 2012.
[42] See, e.g., Easterlin *et al.* 2010, 2012, Princen *et al.* 2002, Layard 2005, Whybrow 2005, Victor 2008, Schor 2010.

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