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Stumbling towards sustainability

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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, with most of the rest unavailable, leaving only 9% for potential future growth in human use (Running 2012). Humanity has exceeded sustainable boundaries for greenhouse gases (GHGs), nitrogen, biodiversity loss, and other key resources and ecosystem services (Rockstrom et al. 2009). The global ecological footprint of humanity is now 1.5 times the sustainable carrying capacity of the Earth (Wackernagel et al. 2002, as updated at http://www.footprintnetwork.org). At the same time, population is expected to grow by 2 billion by 2050 and the world economy 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, from organizations and firms to industries to economies to society to our personal values.

At the organizational level, many firms are pursuing 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: reducing costs and environmental impact simultaneously. 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 ecologically and economically?

At the national and international levels, legislation and agreements to reduce unsustainability have proven extremely difficult, particularly for important common pool resources such as GHGs. Despite the theory for and some examples of effective management of common pool resources

(Ostrom 2010), national and international agreements and policies for critical issues including deforestation, fisheries and climate change, among others, remain out of reach and for many of these the prevailing attitude among policymakers, scholars and citizens alike is pessimism and despair (e.g., Randers 2012, Hickman 2010, Meadows 2012).

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 products and industries arise, if agreements to reduce GHG emissions are adopted, will they actually move our society towards sustainability, or simply lead to direct and indirect rebound effects, with greater consumption overwhelming greater ecoefficiency?

Where are the high leverage points to implement successful change programs, transform existing organizations, industries, and personal values, and address overconsumption? What change strategies are likely to work at each level, how do they differ and interact? What can leaders in each domain do to build a more sustainable world?

Characteristics of Complex Systems

Climate change, water shortage, persistent pollutants, species extinction—the all too familiar litany of environmental crises—are not the problem. They are symptoms. Beneath the unsustainability of human society lies a widespread failure of systems thinking (Sterman 2000, 2012, Meadows et al. 2004, Forrester 1971a, b). Where the consequences of our actions spill out across space and time, we tend to focus on the short term. Where complex systems are dynamic, our mental models tend to be static. We divide the world into silos, ignoring interconnections. But interconnectedness is the essence of a complex system: We cannot have healthy companies, a healthy economy, and healthy people if the pursuit of profit destroys the environment; we cannot have a healthy environment if people live in poverty, without decent housing, healthcare, education and opportunity.

The challenge of building a sustainable world lies in moving from slogans about systems to specific tools and processes that help us understand complexity, design better policies, facilitate individual and organizational learning, and catalyze the technical, economic, social, political and personal changes we need to create a sustainable society.

First, I describe the characteristics of complex systems that lead to policy resistance—the tendency for our attempts to solve problems to be defeated by unintended reactions of the system to these interventions. Policy resistance arises from the gap between the complexity of the systems in which we live and the often simplistic and erroneous mental models of those systems that guide our decisions and behavior, from the short time horizons we consider, and from the fragmentation of knowledge into disciplinary silos (Forrester 1969, 1971a, Sterman 2000). Forest fire prevention and suppression policies work in the short run, but as a consequence of initial success, the fuel burden builds, increasing the incidence and severity of fires. Buying vehicles with better gas mileage in response to high gasoline prices reduces the demand for petroleum, lowering gas prices and undermining the demand for more efficient cars. Powerful pumps help farmers access deep aquifers in arid regions, but speed the drop in the water table, reducing water availability. In these and many other cases, our best efforts to solve problems often make them worse (Table 1).

Policy resistance arises from a mismatch between the characteristics of complex systems and the simplistic mental models we use to make decisions (table 2). Where the consequences of our actions spill out across space and time, we tend to focus on the local and short term. Where complex systems are dynamic, tightly coupled, governed by feedback, nonlinear, self-organizing, adaptive and evolving, our mental models tend to be static and narrow. We ignore interconnections and the delayed and distal impacts of our decisions. We divide the world into silos, whether a firm, with separate and often competing fiefdoms of sales, production, finance, research and so on, governments with separate departments of energy, interior, agriculture, transportation, and so on, or universities with separate departments and disciplines.

Dynamics of Growth in a Finite World

One of the most pervasive and damaging failures of systems thinking is the belief that growth and sustainability are compatible. But sustainable growth is an oxymoron. We live on a finite world, a materially closed, thermodynamically open system. Herman Daly (1991) articulated three fundamental, necessary conditions for sustainability in any finite environment, shown in Figure 1 using standard stock and flow notation. In a sustainable society, (1) renewable resources cannot be used faster than they regenerate, (2) pollution and wastes cannot be generated faster than they decay and are rendered harmless; and (3), in the long run, nonrenewable resources cannot be used at all. These principles follow directly from the fundamental laws of accumulation: If a bathtub is drained at a higher rate than it fills, the level of water will fall; in exactly the same way, a sustainable society cannot harvest cod faster than they reproduce. Filling a tub faster than it drains raises the level of water, so a sustainable society cannot produce greenhouse gases faster than they are removed from the atmosphere. And the level of water in a tub with an open drain but no inflow will fall until the tub is empty, so a sustainable society cannot rely on nonrenewables such as fossil fuels.

Our society is far from meeting any of these three fundamental requirements for sustainability (Wackernagel *et al.* 2002, Rockstrom *et al.* 2009, Running 2012). And growth in population and affluence is rapidly deepening unsustainability.

Many people believe that the challenge of creating a sustainable society can be met through technological innovation. Technology, it is argued, is already improving energy efficiency, reducing waste and creating new products and services that will reduce the human ecological footprint to sustainable levels. Advocates of what I will call the strong form of technological optimism (e.g., Julian Simon 1996) argue that technological innovations to address environmental problems and create a sustainable society arise naturally through the normal functioning of the market system as it now exists (or would, if government would cease interfering with the market), so that the best way to pursue sustainability is to continue business as usual policies directed especially at economic growth. The weak form of the technological optimism argument recognizes that policy changes are required to stimulate the innovations needed. Weak form technological optimists believe innovation can solve the problem of unsustainability, but only with the right incentives, such as subsidies or tax credits for green industry or Pigouvian taxes to correct negative environmental and social externalities.

The IPAT framework (Impact = Population * Affluence * Technology (Ehrlich and Holdren 1971, Chertow 2001) provides a useful decomposition of the potential sources of improvement to address the potential for technology to address the problem. As an example, Figure 2 applies the IPAT framework to climate change, where impact is measured in gigatons of CO_2 emissions per year:

$$\underset{(\text{GtCO}_2/\text{year})}{\text{Emissions}} = \underset{(\text{People})}{\text{Population}} * \underset{(\$/\text{person/year})}{\text{GDP per Capita}} * \underset{(\text{CO}_2/\$)}{\text{Emissions Intensity of GDP}}$$

Since 1950 better technology and changes in the composition of the gross world product reduced the carbon intensity of the economy at about 1.2%/year, though actual CO_2 intensity has been rising since about the year 2000, primarily due to the emergence of China, India, and other rapidly developing nations. Despite falling carbon intensity, however, population growth (from 2.5 billion in 1950 to 7 billion in 2010) and rising affluence (an average growth rate in output per capita of about 1.7%/year) overwhelmed the improvement in technology, so global CO_2 emissions from fossil fuels rose from less than 6 $GtCO_2$/year in 1950 to about 33 $GtCO_2$/year in 2010.

Projecting emissions through 2100 using the 2010 UN medium fertility population forecast (9.3 billion by 2050, 10.1 billion by 2100) and projecting continued change in both income per capita and the carbon intensity of the economy at their historic rates since 1950 yields projected CO_2 emissions of 85 $GtCO_2$/year by 2100. That figure is optimistic because carbon intensity has been rising since the 2000s, and total global emissions are now above and rising faster than IPCC SRES scenarios such as A1FI and A1B in which emissions exceed 100 $GtCO_2$/year by 2100 (IPCC 2007). In contrast, limiting expected climate change to the 2°C target adopted by the nations of the world through the UNFCCC would require global CO_2 emissions to fall roughly 80% from current levels by 2050, with continuing declines thereafter (http://climatescoreboard.org, UNEP 2011). Achieving such reductions through technology alone would require an average rate of decline in the carbon intensity of the economy greater than 4%/year, starting immediately. That 4%/year figure is not the rate of improvement needed in the marginal carbon intensity of new investment, but the rate of decline in average carbon intensity, which depends on the installed base of long-lived energy producing and consuming capital stocks, and even longer-lived attributes of our society including dominant designs for basic products and infrastructure, such as personal automobiles with internal combustion drive trains, the oil supply chain to provide the fossil fuels they require, and extensive road networks and settlement patterns requiring people to drive from their homes to jobs, services, education and entertainment.

Sustainability cannot be achieved through technological innovation alone, and certainly cannot be achieved through modest changes to business as usual trends, policies and prices. Improvements in technology that reduce impact per unit of economic activity are vitally important. But they are not sufficient. Population and especially growth in consumption per person must also be addressed.

To begin, however, consider how fast technological change can reduce impact, first within existing organizations, then in the creation of entirely new industries.

Sustainability as Product and Process Improvement

Nearly all firms now seek to reduce 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 new, 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. Whether stakeholders are more or less motivated to participate in sustainability initiatives given such altruistic framing remains an open question.

Across nearly all industries and firms, the unit costs of production, product capabilities, and other product and process attributes steadily improve through processes of learning by doing, investment in R&D, assimilation of feedback from customers, and other means (Argote 2013, Nagy et al. 2013). Improvement rates also vary significantly, both within and across firms. Improvement is always subject to diminishing returns: over time, improvement rates slow as the "low hanging fruit" is picked and as performance approaches physical limits.

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" here includes any characteristic of a process that leads to waste including product defects, safety incidents, unit costs, process cycle times, and other traditional business metrics, as well as energy consumption, pollution and solid waste generation, and other metrics relevant to sustainability. Figure 3 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.

After the assembly plant initiated an improvement program, the manufacturing cycle time fell rapidly, from over 100 hours to about one (two-shift) workday, with an average improvement half-life of about 1.5 years. In contrast, US auto fatalities grew from the start of the industry to a peak of 45 per 100 million vehicle miles traveled (VMT) in 1909, then fell to about 1.1 per 100 million VMT by 2010, an average improvement half-life of about 21 years. Note that the actual rate of decline from 1909 through the early 1920s exceeds the best-fit exponential as the low hanging fruit of safety improvements was picked, including vehicle controls (brakes, lights, etc.), road signage, driver licensing and training and so on.

What accounts for the difference in improvement half-lives? Sterman, Repenning and Kofman (1997), consistent with other theories of organizational learning and quality improvement (e.g. Argote 2013, Zangwill and Kantor 1998), note that improvement arises as the result of an iterative process in which workers search for and experiment with new ways of carrying out tasks, select and adopt those that produce improvement, then search for additional improvements, etc. 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 the PDCA (Plan-Do-Check-Act) or Shewhart-Deming cycle. Figure 4 shows the core feedback structure governing improvement processes. Whether formal or informal, the fractional improvement rate for any process, ϕ, is determined by the cycle time for each iteration of the learning cycle, λ, and the fractional improvement achieved per cycle, i:

$$\phi = i/\lambda$$

Assuming no new defects are introduced over time (an assumption relaxed below), the level of defects, D, is governed by

$$dD/dt = \textit{Defect Elimination} = -\phi\,(D - D_{min})$$

where $D_{min} \geq 0$ is the minimum possible defect level. The iterative learning process that leads to defect elimination forms the balancing (negative) *Improvement* feedback labeled B1 in Figure 4. Assuming a constant improvement half-life, the dynamics of the defect level are:

$$D_t = D_{min} + (D_{t_0} - D_{min})\exp(-\phi(t - t_0))$$

and the improvement half-life is $\ln(2)/\phi$.

Improvement half-lives vary across processes and over time. Sterman *et al.* (1997), following Schneiderman (1988), 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 (e.g., the operator, perhaps a mechanic), while improving the tooling for 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.

In simple processes, cause and effect are easily discerned. The improvement process requires only a few people and few organizational boundaries are crossed. Experiments can be designed, executed and evaluated quickly. The learning cycle time will be short and learning per cycle will be high; the improvement half-life will be short. As technical and organizational complexity increase, experiments become difficult and time consuming, the interpretation of results is confounded by covariation in more variables, and problem solving requires the cooperation and coordination of increasing numbers of people, functions and organizations. The learning cycle time increases and learning per cycle falls, leading to longer improvement half-lives. Schneiderman (1988) found that improvement half-lives were 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.

Considering the examples here, 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 tooling, then reducing buffer stocks of WIP inventory between workstations. Doing so required the participation of relatively few workers, engineers, and low-level managers, all from the same facility.

In contrast, automobiles are technically complex, with tight couplings among major subsystems both within the vehicle, including drive train, suspension, sensors and controls, and between the vehicle and driving environment, including road design and condition, 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 from component suppliers from tires and glass to windshield wipers and headlights. 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, citizen groups and other actors, automakers have shaped technology, regulations and legislation affecting safety such as seat belts and air bags. Many improvements in safety arose from innovations in road design, signage, traffic laws, insurance regulations, licensing requirements and driver training, and hence involve local, state and federal government, insurers, schools, parents and the public at large. Such high technical, organizational and political complexity leads to a much longer improvement half-life for automotive safety compared to improving manufacturing processes within a plant.

Improvement half-lives are not constant over time. Typically, as the easy improvements are made, the technical and organizational complexity of the next improvement effort increases, shown in Figure 4 as the balancing *Low Hanging Fruit* feedback, B2. Thus not only does the absolute improvement in performance decline over time, but the fractional rate of improvement can slow. 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 12 years, and 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. Later innovations (air bags, antilock brakes, traction control, stronger social norms against drunk driving) involved far greater technical and organizational/political/social complexity.

Figure 5 qualitatively maps different sustainability issues into the space of technical and organizational/political complexity. Many energy efficiency and waste reduction programs at the levels of individual organizations, for example, have very low complexity on both dimensions, and the data show that there are many such opportunities with very short payback times, high ROI, and positive net present value (Porter and van der Linde 1995, McKinsey 2010, Lovins 2012, Lyneis and Sterman 2013). 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 a contractor, solar suppliers, installers, and local governments who provide permits for 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 production 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. The challenge of creating a sustainable, low-carbon automobile fleet involves envelope-pushing technical complexity (electric vehicles, batteries, supercapacitors, fuel cells) but also requires society-wide coordination among automakers and their supply chains, fuel infrastructure providers, governments, and other actors required to build critical complementary assets including fueling infrastructure and supply chains, develop consumer awareness and acceptance of new technologies, develop standards for, e.g., vehicle charging, and so on (see below and Struben and Sterman 2008). Ethical production including decent wages and healthy, safe workplaces is technically simple—there is no technical challenge in providing fire alarms and unchaining emergency exits in garment factories—but involves coordination across multiple actors including clothing and electronics retailers, their suppliers, unions and labor activists, NGOs and third-party monitors, governments, and others in a globalized economy (Locke 2013). Sustainable management of common pool resources such as forests, fisheries and the climate offers moderate technical complexity, but very high organizational and political complexity, often requiring multi-scale, polycentric governance extending from the local, community level to the global level of international agreements and treaties (Ostrom 2010). Finally, reducing overconsumption is not particularly complex technically, but poses major social and political challenges within and across nations and societies.

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, including sourcing, product use, and disposal, while essential, will prove to be more difficult. Walmart provides a typical example (Plambeck 2010, Humes 2011): energy efficiency and waste reduction initiatives were notably successful, while more complex supply chain initiatives had mixed outcomes, including some failures (organic cotton, sustainable seafood, RoHS-compliant electronics sourcing, e-waste take-backs), and Walmart chose not to address organizationally and politically complex issues such as ethical sourcing and working conditions (Humes 2011), 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 (Greenhouse 2012).

Rebound effects and moral licensing

So far the model assumes that the level of defects in a process can only fall as improvement occurs. However, defects are continually introduced into processes as conditions change, rendering existing practices, technology, skills and behavior obsolete. Most important for the present purpose, defects can arise as endogenous consequences of improvement. By lowering the costs and risks of an activity, improvement often triggers changes in people's behavior that offset the benefits of learning. Such direct rebound effects (Sorrell et al. 2009, Herring and Sorrell 2009) and processes of risk homeostasis (Wilde 2001) are common. Figure 6 expands the boundary of the model to capture such rebound effects in two ways. First, as defects fall and the performance of the organization's products and processes improve, actors in the affected system will find new uses for the product, engage in new behaviors, and face new operating conditions. These changes introduce new defects into the process, undermining the improvement (the balancing *Direct Rebound Effect* feedback B3). Better tires, brakes, and roads improved automotive safety, but these very improvements led people to drive faster, leave less space between themselves and traffic ahead and corner more aggressively, undermining some of their benefits (Wilde 2001). Second, better, cheaper, more capable products and processes stimulate demand and increase total product use. Endogenous improvements in automobile safety, costs, reliability and features, better and more extensive roads and the decentralized settlement patterns they enable, along with rising population and affluence, led to such a large increase in VMT per year that annual automotive fatalities in the US rose over the last 100 years by more than a factor of 20 despite a forty-fold reduction in the risk of death per VMT. Greater vehicle efficiency lowers the cost per mile of driving and leads to an increase in VMT.

A more troubling behavioral reaction to sustainability improvements arises outside the price system. Catlin and Wang (2013) found "consumers used more paper while evaluating a pair of scissors when the option to recycle was provided (vs. not provided) [and that] per person restroom paper hand towel usage increased after the introduction of a recycling bin compared to when a recycling option was not available." The increase in consumption cannot be attributed to lower costs per unit of paper. Instead, it appears to arise from "moral licensing" in which behaviors people interpret as pro-social or involving personal sacrifice for the greater good build up a psychological credit, a "get out of jail free card" (Bolton et al. 2006) allowing them to engage in selfish or anti-social behavior without feeling guilt or shame. If the paper towels will be recycled, why not use another one? If I buy an alternative fuel vehicle, why not go by air on my next vacation? If I had an organic salad for lunch, how about a nice, juicy steak for dinner?

Direct rebound effects can be moderated or eliminated by taxes or feebate programs that, for example, raise the cost of driving to offset the reduction in the cost per VMT created by greater fuel efficiency. Rebound effects due to moral licensing are likely more difficult to correct through policies that affect the cost of the activity. The leverage here is likely to be in changing the norms through which people assess behavior. If people believe recycling is a sacrifice or an unusual, pro-social act, they may feel entitled to increase their consumption or waste in other areas. If, however, recycling becomes the standard, default behavior, something everyone does as a matter of course, then engaging in it no longer builds up a credit you can use to be wasteful or lazy in other areas, while violating it becomes a deviant act that risks feelings of guilt or social sanction.

The Capability Trap

The model above suggests why improvement rates vary across industries and processes and how complexity and rebound effects can slow learning and improvement below the rates that are required to respond to the urgent sustainability challenges we face. However, there in many situations improvement and learning are not taking place even at the potential rate. Numerous studies demonstrate that individuals, firms 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 (e.g. Porter and van der Linde 1995, McKinsey 2010, Lovins 2012, Lyneis and Sterman 2013). 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" (Olson and Fri 2008, p. 80). McKinsey (2010), 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 waste and energy use, and improve sustainability go unimplemented.

Why are profitable investment 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 (Gillingham et al. 2009).

Other explanations 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 (Jaffe & Stavins 1994, Howarth & Sanstad 1995).

Others stress the role of behavioral and organizational biases, including the sunk-cost fallacy, the low salience of future savings compared to the up-front costs of investments, inconsistent time preferences and organizational silos (Bazerman 2009, Yates & Aronson 1983, Frederick, Loewenstein & O'Donoghue 2002). 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, replace inefficient lightbulbs only when they burn out even when early retirement is profitable, 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 (Rahmandad 2012, Repenning & Henderson 2010).

Certainly, the costs of some improvement opportunities are underestimated, and principal-agent problems, information asymmetries, management biases and short-termism influence 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 (Beer et al. 1990, Easton and Jarrell 1998, Repenning & Sterman 2002). Persistent performance differences in seemingly similar enterprises (PPDs in SSEs) are common. From airline kitchens (Chew et al. 1990) to health care (Wennberg 2010), similar firms in the same industry, units within the same firm, and even different floors of the same building exhibit PPDs despite powerful financial incentives for improvement, market forces favoring high performers, the wide availability of process improvement tools and methods, knowledge flows, and other mechanisms that should lead to widespread adoption and implementation of best practices (Gibbons and Henderson 2012, 2013). 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 (Syverson 2011).

One common failure mode for process improvement is the *capability trap* (Repenning and Sterman 2001, 2002, see also Keating et al. 1999). Figure 7 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, monitor the performance of that process against the 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 in proper procedures (working faster by 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, the organization can interpret the performance gap as a sign that the organizations' 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 technical improvement tools and human capital, including skills, cooperation, and trust. Investing in capability improvement forms the balancing Work Smarter feedback (B5).

The improvement half-life now depends not only on the technical and organizational complexity of the process, but on the intensity and effectiveness of improvement effort (Sterman et al. 1997). 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 (Repenning and Sterman 2002, p. 282-283).

The result is the reinforcing feedbacks denoted "Reinvestment or Ruin" (R1a and R1b). As the name suggests, these feedbacks can operate either 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, however, if managers respond to a performance gap by increasing pressure to do work, workers increase the amount of time spent working, the time spent on improvement falls, and the organization's improvement capabilities decay. Eventually, defect elimination falls below the rate at which new defects are introduced by changes in products, processes, personnel and other conditions, increasing the throughput gap further and forcing an even larger shift towards working harder and away from improvement. The vicious cycle quickly drives out any meaningful improvement activity and can lead to such low capabilities and poor performance that the organization fails.

Many believe that an organization would never allow itself to fall into the capability trap: after all, "everyone" knows that "an ounce of prevention is worth a pound of cure", "a stitch in time saves nine" and so on; since at least the quality revolution of the 1980s, businesses claim to understand that it is far better and cheaper 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. Working longer hours, speeding the line, 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 8 illustrates using the example of maintenance in a manufacturing plant (Repenning and Sterman 2001, 2002, Carroll, Sterman and Marcus 1998). 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, or else plant uptime falls and customer commitments cannot be met. Instead, proactive maintenance and improvement suffer, along with investments in capabilities such as training, part quality, design improvement efforts, and, all to often, adherence to safety protocols. The first impact? Maintenance costs fall, closing the budget gap. 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, wear and operating conditions introduce new ones. The rate of breakdowns and failures grows, increasing the reactive maintenance workload and costs, further lowering proactive maintenance and improvement. 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 (2009) 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….Correspondence dating to as early as 1961 indicates that management and refinery personnel were aware of the explosive nature of sugar dust and the importance of minimizing dust accumulation….
>
> [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 secondary dust explosions, rapid spreading of the fires throughout the facility, and resulting fatalities would likely not have occurred if Imperial Sugar had enforced routine housekeeping policies and procedures…."

The power of the performance gap to pressure people to work harder at the expense of maintenance, improvement and safety is illustrated by a 2005 memo sent to all Massey Energy employees by then-CEO, Donald Blankenship (Fisk, Sullivan & Freifield 2010):

> "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."

Now consider what happens when an organization seeks to escape the capability trap. Figure 9 shows the plant illustrated in figure 8, 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. Costs rise, of course, because the maintenance group must increase the level of preventive and scheduled 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, the increased improvement effort and gradual growth in improvement capabilities eventually begin to eliminate defects 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 defects requires either an increase in total costs so that improvement effort can increase while maintaining current output, or cutting output in the short run by reallocating existing resources from production to improvement.

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 defects cut. 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 and waste reduction programs fall into this category. MIT, for example, has gradually fallen into the capability trap with respect to maintenance, 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 (Lyneis and Sterman 2013). 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 (Halber 2010). 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. Sterman et al. (1997) show how 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 (see also Repenning 2002).

The short- and long-run impacts of policies are often different (Forrester 1969, Sterman 2000, Repenning and Sterman 2001) 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 far longer than the fishing community can survive. Converting a farm from conventional to organic production can 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 initiatives 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. Many proposed initiatives, even those 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, and 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. Organizations, from for-profit firms to governments, appear to be learning that they should defer or avoid such efforts, as illustrated by Walmart's sustainability experience. Focusing on quick wins and high payoff processes is locally rational, and waste reduction and energy efficiency programs, for example, are essential in building a more sustainable world. But they are not sufficient. The capabilities and persistence needed to mitigate technically and organizationally complex sustainability challenges will not develop if organizations believe that they cannot sustain the investments needed to succeed in these areas, even when they are essential for firm, and societal, survival. Eroding capabilities then worsen the WBB behavior those organizations would experience if they were to implement programs to address the technically and organizationally complex issues, a vicious cycle of eroding goals and low ambition that has led, for example, to widespread cynicism about the prospects for global action to mitigate GHG emissions.

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 likely to be 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. Electric or hydrogen powered vehicles will displace internal combustion vehicles powered by gasoline. Organic, local, small-scale agriculture will displace factory farms and monocultures.

The history of such transitions is one of false starts, delays, unpredictability, and path dependence. 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.[1]

A wide range of alternative drive train and fuel technologies are now contending to be the new dominant design, including electric, hydrogen ICE, hydrogen fuel cells, ICE powered by ethanol, methanol, and biofuel blends such as E85, compressed natural gas (CNG), and combinations thereof, including conventional and plug-in hybrids, powered by gasoline, diesel, E85, or biofuels. The history of attempts to introduce alternative fuel vehicles can be characterized as "Sizzle and Fizzle" (Figure 10). Multiple attempts to (re)introduce electric vehicles have failed (Hard and Knie 2001). 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 (Flynn 2002).

The failure of AFV programs to date is commonly attributed to high costs and immature technology. Certainly the high cost and low functionality and variety of AFVs compared to fossil-ICE limits their market potential today, particularly in nations like the US where gasoline is priced 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, as shown by Struben and Sterman (2008), that sustained AFV adoption would be difficult even if AFV performance equaled that of ICE today.

The enormous scale of the automobile industry, fleet and associated complementary assets creates a set of powerful positive feedback processes that confer substantial advantage to the incumbent fossil-ICE technology (Figure 11). First, AFVs including electrics, hydrogen, CNG and biofuels require new fueling infrastructure incompatible with the existing fuel supply chain and retail

[1] Projections based on US data for 2008.

distribution network. Drivers will not buy AFVs attractive 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 despite limited fueling infrastructure: 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, already 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).

Demand for AFVs is significantly conditioned by word of mouth, social exposure to the vehicles, and other social processes (Struben and Sterman 2008). Keith (2012) 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, capacity, 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 11 also shows the principle policy levers available to industry actors and governments to stimulate the AFV market, including subsidies offered to consumers by either government (e.g., 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 higher gasoline taxes or carbon prices that push up the prices of gasoline and diesel. 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 (Struben and Sterman 2008, Keith 2012) 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.

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, flexfuel, CNG and hydrogen powered vehicles, and leading OEMs including GM and Ford are pursuing an "all of the above" strategy, offering and developing a wide portfolio of different AFVs. But hedging bets due to the uncertainty around the next dominant design delays 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 (bus, light rail, high-speed intercity rail), 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. However, current political sentiment in the US, at least, eschews government intervention and especially government subsidies that appear to be "picking winners and losers."

Overconsumption

Suppose, despite the barriers described above, that learning and improvement within incumbent organizations accelerate, that the coordination and standards required to bootstrap the emergence of new, sustainable industries occurs swiftly, that direct rebound effects are mild and that the market failures plaguing common pool resources, from forests to fisheries to water to the climate, are resolved. What happens if market forces and innovation overcome the resource scarcity, pollution, and other threats to our welfare and lives, and do so in time, before the carrying capacity of the world collapses? Would we then be on the road to a sustainable society? Unfortunately the answer is no.

Humanity has already overshot the sustainable limits to growth. 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. Figure 12 expands that framework to show the feedbacks between the global carrying capacity and human activity. On the left, human activity grows through reinforcing feedbacks of population and economic growth (aggregated into reinforcing loop R1). Growth in human activity is constrained by the adequacy of resources (the ensemble of nonrenewable resources, renewable resources, and a healthy, clean environment). As population and economic activity grow relative to the carrying capacity, the adequacy of those resources declines. Sufficient decline in resource adequacy lowers the net fractional growth rate in human activity, eventually causing growth to stop via the *Involuntary Limits to Growth* (loop B1).

If the carrying capacity were constant growth would follow an S-shaped pattern in which resources per capita fall until they are just scarce enough to balance births with deaths: a subsistence equilibrium in which life would be nasty, brutish and short. That naïve Malthusian model is simplistic because the carrying capacity of the earth is dynamic. On the one hand, the larger the population and the greater the economic impact of each person, the greater the consumption and degradation of the carrying capacity: a larger, richer population consumes more resources, generates more waste, uses more fossil fuels, emits more greenhouse gas emissions, etc., forming the balancing *Resource Consumption* loop, B2). On the other, the carrying capacity can regenerate: logging provides more light and nutrients for seeds and saplings; composting and nitrogen fixing bacteria can restore soil fertility; DDT and dioxin eventually break down into harmless compounds. These processes are captured by the balancing *Regeneration* loop B3. Of course, there are delays in the regeneration process: acorns require decades to become mighty oaks; soils form at rates of a few millimeters per year; DDT degrades over decades. And some elements of the carrying capacity cannot be regenerated: fossil fuels and high-grade copper ores are nonrenewable; extinction is irreversible; stocks of plutonium and other nuclear wastes will remain with us far longer than any civilization on earth has yet endured.

Even for the renewable elements of the carrying capacity there are limits to regeneration and restoration. Harvest a few cod and the population recovers, but take too many and the population collapses; take a few trees and the forest regenerates, but clear cutting can alter rainfall and surface albedo so that the land becomes savannah or desert. These processes are captured by the reinforcing *Environmental Tipping Point* feedback R2: degrade the earth's carrying capacity too much and its ability to regenerate withers, accelerating the collapse in a vicious cycle. Where these tipping points lie is usually uncertain—until they have been crossed, by which time it is too late.

If regeneration is rapid and regeneration capacity robust (loop B3 is strong and swift and the tipping point loop R2 is weak), and if renewable substitutes for nonrenewables can be deployed in time, then regeneration quickly rises to offset resource consumption and waste production and the decline in the carrying capacity is slight. However, if regeneration is weak and slow, or the tipping points strong and close, then carrying capacity will fall. The system does not reach equilibrium when the carrying capacity and human activity meet. Instead, consumption and degradation of the carrying capacity exceed regeneration, so the carrying capacity of the earth continues to fall. As it does, economic output and/or human population must fall. In the extreme, if the population remains dependent on nonrenewable resources or generates wastes that cannot be dissipated, the carrying capacity must continue to fall as long as there is any remaining activity, and the only equilibrium is zero population—extinction. Incorporating the dynamics of the carrying capacity changes the system dynamics from S-shaped growth to overshoot and collapse (Forrester 1971b, Meadows *et al.* 2004).

The model in Figure 12 also includes the impacts of the price system and technological innovation. As a resource becomes scarce, its price rises, which should stimulate technical innovation that cuts demand and substitute more abundant resources for those that are scarce (e.g., drilling deep offshore oil wells in the Gulf of Mexico as shallower deposits on land are depleted; boosting the gas mileage of autos); these responses form the balancing *Technological Solution* feedback, B4. That feedback also includes the possibility that scarcity may induce governments to increase research and development (e.g., R&D on alternative energy sponsored by the US Department of Energy), and correct market failures through regulation, stimulating innovation (e.g., CAFE standards and the cap and trade market in SO_2). Further, social norms may change in response to scarcity (e.g., recycling).

There are, however, important lags in these technological solution feedbacks, including delays in the detection of environmental problems, in recognizing the opportunity for profit when prices rise, and in the reallocation of capital and R&D resources. There are long delays before R&D yields new technologies, and between laboratory demonstrations and commercialization. Once new technologies reach the market, there are even longer delays in adoption and the replacement of old infrastructure, and further delays before the carrying capacity responds.

Many technologies create unintended effects that intensify scarcity or environmental problems elsewhere. Taller smokestacks on Midwestern power plants reduced smog in Ohio and Pennsylvania, but caused to acid rain in New York and New England; the Haber-Bosch process to fix nitrogen led to synthetic fertilizer, boosting crop yields (where farmers could afford it), but consumes huge amounts of fossil fuels while fertilizer runoff eutrophies rivers and lakes and creates dead zones in offshore waters. These unintended harms create the reinforcing "Technological Nightmare" feedback R3: as before, scarcity and environmental degradation caused by growth in human activity lead to higher prices for the affected resources, along with government and social responses. The resulting technological solutions have some benefits, but also lead, usually after delays, to harms that accelerate the erosion of the carrying capacity, leading to greater scarcity and new environmental problems, triggering still higher prices and still greater attempts to find a technological solution, in a vicious cycle.

The strength of, delays in and unintended harms from technological solutions are strongly conditioned by the effectiveness of the learning and market development feedbacks discussed above: high technical, organizational and political complexity, capability traps and market failures can slow or thwart the market and social response to scarcity.

Clearly, if markets are imperfect, if the delays in the social, economic and technical response to scarcity and environmental degradation are long, or if the harmful so-called side effects of technology dominate the benefits, then the result will be overshoot and collapse: technological solutions will be "too little, too late" or will actually worsen the problem. The global carrying capacity will fall until human population and economic activity drop enough to balance the draw on resources and the generation of wastes with the ability of ecosystems to regenerate them and render pollutants harmless.

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? Successful responses to scarcity and environmental degradation, by increasing the adequacy of resources and lowering prices, enable population and economic output to grow still further, reducing the adequacy of resources directly (loop B1) and indirectly, by increasing the rate of consumption and degradation of the carrying capacity (loop B2). The result: society is once again pushed up against one environmental limit or another. If markets and technology once again succeed in addressing those new limits, then human activity grows still further. To avoid involuntary limits to growth through technology, one must assume that technological solutions to all resource and environmental problems can be found, that the costs of these solutions are so low that they don't constrain economic growth, that the delays in the recognition of problems, in the innovation process, in adoption and diffusion of new technologies, and in the response of the carrying capacity are always short, that these solutions never generate significant unintended harms, and that technological solutions keep the carrying capacity from crossing important environmental tipping points. Most important, one must believe that, eventually, both population growth and people's desire for more income and wealth will end. If any of these conditions fail, then the carrying capacity will eventually drop, leading to overshoot and decline.

As is typical in complex systems, much of the debate between environmentalists and technological optimists focuses on the symptoms of the problem: resources and the resiliency of the environment. How much oil is there? How much solar power can be produced? How much copper can be mined, and at what costs? And so on. That debate misses the point: it makes no difference how large the resource base is: to the extent technology and markets alleviate scarcity today, the result is more growth tomorrow, until the resource is again insufficient, some other resource becomes scarce, or some other environmental problem arises. Solve these, and growth continues until some other part of the carrying capacity is lost, some other limit reached. As long as growth is the driving force there can be no purely technological solution to the problem of scarcity. 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 (the balancing *Voluntary Limits* loop B5 in Figure 12).

Population growth may stabilize "voluntarily" through the demographic transition (e.g., Caldwell 2006, but see the cautions in Dasgupta and Ehrlich 2013). The UN's 2010 projections assume that the demographic transition will continue throughout the world, including the least developed nations, nearly stabilizing by 2100 at more than 10 billion. But even if population growth eventually stops, human impact on the environment will not: economic growth is projected to continue, and as the production of goods and services per capita rises, so too will the impact of each person. Resource use and environmental impact per person cannot fall to zero—people need a minimum amount of food, water, living space, energy, and waste disposal capacity, among other resources. The only way total impact can stabilize is for both population and economic output per person to stabilize. Yet no nation on earth seeks to end the growth of its economy.

Avoiding decline in population or economic output will require all the technical and social innovation we can muster. We urgently require technologies to replace fossil fuels, cut greenhouse gas emissions, boost food production without use of toxic pesticides, create new antibiotics as pathogens evolve resistance, end deforestation and protect biodiversity. We urgently need to create more effective markets to capture environmental and social externalities, providing businesses and consumers with the price signals that will drive innovation and stimulate efficient use of resources. We urgently require better science, environmental monitoring, and product testing so that the new technologies we develop don't create unintended consequences that worsen the very problems we seek to solve. But while necessary, technological innovation alone is not sufficient. We must also ask how much is enough. How much wealth, how much consumption do we each require?

With a few important exceptions (the work of Herman Daly and colleagues, e.g., Daly and Townsend 1993; see also Princen *et al.* 2002, Meadows *et al.* 2004, de Graaf *et al.* 2005, Whybrow 2005, Victor 2008, Schor 2010), most of the research, teaching and popular discourse on sustainability continues to focus on technological solutions—more energy, more resources, more efficient eco-friendly growth, while the actual leverage point—voluntarily limiting our consumption—remains largely undiscussable, particularly among our business and political leaders. That conversation is not an easy one. For many years I have asked my students "how much is enough" (Table 3).

Typical of results with diverse groups, the median response to Question 1 of 109 students at the MIT Sloan School of Management (primarily MBA students) in the fall term of 2010 was $200,000/year. The mean was over $2 million/year, skewed by 14% whose responses were $1 million/year or more. *Spending* $2 million (or even the median estimate of $200,000) per year dwarfs mean per capita *income* in the United States, with GDP per capita of $46,650, much less the GDP per capita of most African nations, which remains less than $1,000/year (2008$; see hdr.undp.org/en/statistics). The urge for *more* is strong: about half the students chose "more is always better." Among 156 similar students in my sustainability course in 2009 and 2010, an overwhelming 83% preferred to earn more next year than this year (Question 2). These students know they would be better off taking the extra $50,000 up front (the net present value of World 2 is higher: you could spend the same as in World 1, invest the extra $50,000 and have more than $200,000 the second year). When asked why they chose the less valuable option, many reported that it would be hard to reduce their standard of living if their income dropped, though there is nothing in the question that requires them to spend more in year 1 than year 2. Quite a few said they would feel they had somehow failed, would feel less worthy as a person, if their income dropped, as illustrated by an executive MBA student who wrote that an "increase in salary represents the increase of my value and contributions to the world." Even more disturbing, 58% preferred to earn less each year—as long as they make *more* than everyone else (Question 3). People tend to judge how well off they are by social comparison, and are less happy when others have more than they do (Layard 2005). Of course, this is a zero sum game: everyone cannot be richer than everyone else.

A large literature shows that subjective well being is strongly nonlinear, rising sharply with income per capita for the very poor, then saturating once basic needs are fulfilled (e.g., Layard 2005). Rising income per capita in the US, Europe, and China has not led to increasing subjective well being even as GDP per capita has doubled or, in the case of China, quadrupled (Easterlin et al. 2010, Easterlin et al. 2012). Figure 13 shows feedback structure I hypothesize to underlie the paradox. The core balancing loops B1 and B2 capture the classical economic logic in which a consumption shortfall (consumption below aspirations, determined by basic needs), leads to lower utility (subjective well-being). To solve the problem, people spend more time working, boosting their income, thus closing the gap and improving their utility.

In affluent societies, however, other feedbacks become more important. First, as people become habituated to past consumption, increasing people's consumption aspirations in a search for more and new consumption to achieve the same level of satisfaction (*The Thrill is Gone*, R1). People also set their consumption aspirations by comparing what they have to that of others. The struggle to keep up with the Jones' creates an obvious reinforcing feedback, an arms race of conspicuous consumption (R2), egged on by advertising and the media, which constantly expose us to people more beautiful and richer than we are (R3, *Lifestyles of the Rich and Famous*). As we work ever-longer hours to boost our consumption, however, our leisure and personal time decline. We respond to the time famine with time-saving expenditures such as driving instead of walking, eating out instead of cooking, hiring child care. In the short run these save time, but the extra cost increases our consumption shortfall and requires us to work even longer hours to pay for our cars, restaurant bills, and nannies (R4, *Gotta pay the bills*). As our personal, non-work time erodes, we have less time for what matters most: exercising and staying healthy, spending time with family and friends, developing intellectually and spiritually, helping those in need. As our well being erodes, we tend to compensate by working even harder so as to increase consumption (R5-R7). These feedbacks constitute a capability trap operating at the personal level, one amplified by advertising, fueled by debt, and celebrated by popular culture.

Firms will not be the locus of change to address overconsumption. While waste reduction and energy efficiency are perfectly aligned with Walmart's business model in which cost reductions increase their market share and hence their power over suppliers, workers and governments, leading to still lower costs and still greater market power, we cannot expect Walmart, or other firms, to implement policies designed to reduce their sales. Patagonia, a privately held firm founded and run by devoted environmentalists, challenges customers to join the Common Threads Partnership in which

> "Patagonia agrees to build useful things that last, to repair what breaks and recycle what comes to the end of its useful life. [And] I agree to buy only what I need (and will last), repair what breaks, reuse (share) what I no longer need and recycle everything else" (http://www.patagonia.com/us/common-threads/).

Sensible and worthy advice. Sustainability requires that firms offer products of higher quality, products that can be repaired, products that can be recycled. Yet these actions don't lower consumption, either of Patagonia's products or overall. To the extent customers buy products that last, then repair and reuse what they buy, they will have additional disposable income to spend on other products and services. Just as cost reductions from ecoefficiency are perfectly aligned with Walmart's business model, the common threads initiative is well aligned with Patagonia's model, in which innovative, high quality, environmentally responsible products are sold at high prices, generating resources they reinvest in product innovation, quality, advertising and environmental programs that boost their brand equity and increase sales, particularly in the affluent, progressive segment of the market. Patagonia famously ran a full page ad in the New York Times on Black Friday 2011, the busiest shopping day of the year, urging customers "Don't buy this jacket" (http://www.patagonia.com/email/11/112811.html). Sales rose dramatically. Sustainability requires that we abandon shopping and consumption as entertainment, as therapy, as a substitute for relationships with family and community, as a balm for spiritual wounds.[2] Firms will not be the source of this change, and will vigorously oppose policies that would discourage consumption such as higher sales or value added taxes and co-opt grass roots efforts to live more simply through greenwashing and marketing (e.g., magazines like Real Simple that peddle stuff to those who want to (look like) they are living simply and sustainably).

The feedback dynamics of conspicuous consumption put those who would promote a low-consumption life at a severe disadvantage. Cool, new, must-have products can go viral through word of mouth, social exposure and other reinforcing feedbacks: the more people buy them, the more others see, "like" and tweet about them on social media, leading still more be infected with the desire to get their own. An epidemic of consumption ensues. But those who don't buy generate no word of mouth that can reinforce the desire to avoid the product. Those who mend their clothes or keep their old electronics instead of buying the latest model are much less likely to tell others they have done so. The bias towards consumption is reinforced by the salience of products and the difficulty of detecting whether those products generate genuine well-being. We can see the size of our neighbor's houses but not whether they are happy within them. We can see other's sleek new cars, but not whether their drivers are filled with rage over the traffic in which they are stuck. We can see the expensive clothes of our coworkers, but not whether they are comfortable in their skin, at peace with who they are.

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. Until we learn to end the quest for more—more income, more wealth, more consumption,

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[2] Examples are legion. See any advertisement for beer, cars, toys, jewelry, clothing or chocolate. Particularly egregious examples include Gund's 1992 ad for a teddy bear that says "I… offer unconditional love" (http://www.nytimes.com/1992/02/10/business/media-business-advertising-muttsy-wuzzy-others-join-campaigns-sell-toys.html), and Lucky Magazine's 2012 "Fill the Void" campaign, http://www.thejanedough.com/if-your-kids-call-the-nanny-mom-fill-the-void-by-shopping-according-to-lucky-ad/.

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. 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."

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Table 1. Examples of policy resistance.

- Road building programs designed to reduce congestion have increased traffic, delays, and pollution (Sterman 2000).
- Low tar and nicotine cigarettes actually increase intake of carcinogens, carbon monoxide, and other toxics as smokers compensate for the low nicotine content by smoking more cigarettes per day, by taking longer, more frequent drags, and by holding the smoke in their lungs longer (Tengs *et al.* 2005)
- Health plan policies "limiting what drugs can be prescribed—intended to prevent the unnecessary use of expensive drugs—[are] having the unintended effect of raising medical costs" (Horn *et al.* 1996).
- Antilock brakes and other automotive safety devices cause some people to drive more aggressively, partially offsetting their benefits (Wilde 2001).
- Forest fire suppression causes greater tree density and fuel accumulation, leading to larger, hotter, and more dangerous fires, often consuming trees that previously survived smaller fires unharmed (US Forest Service 2003).
- Flood control efforts such as levee and dam construction have led to more severe floods by preventing the natural dissipation of excess water in flood plains. The cost of flood damage has increased as flood plains were populated in the belief they were safe (Sterman 2000).
- The impacts of large dams "are more negative than positive and, in many cases, have led to irreversible loss of species and ecosystems" (World Commission on Dams 2001, xxxi)
- Antibiotics have stimulated the evolution of drug-resistant pathogens, including multiply-resistant strains of TB, *S. aureus*, and sexually transmitted diseases (Fong and Drlica 2003).
- Pesticides and herbicides have stimulated the evolution of resistant pests, killed off natural predators, and accumulated up the food chain to poison fish, birds, and, in some cases, humans (Palumbi 2001).
- Despite dramatic gains in income per capita and widespread use of labor-saving technology, Americans have less leisure today than 50 years ago and are no happier (Layard 2005, Kahneman *et al.* 1999).

Table 2. Policy resistance arises because systems are

- **Constantly changing:** Heraclitus said, "All is change." What appears to be unchanging is, over a longer time horizon, seen to vary. Change occurs at many time scales, and these different scales sometimes interact. A star evolves over billions of years as it burns its hydrogen fuel, but can explode as a supernova in seconds. Speculative bubbles can inflate for years, then pop in a matter of hours.
- **Tightly coupled:** The actors in the system interact strongly with one another and with the natural world. Everything is connected to everything else. "You can't do just one thing."
- **Governed by feedback:** Because of the tight couplings among actors, our actions feed back on themselves. Our decisions alter the state of the world, causing changes in nature and triggering others to act, thus giving rise to a new situation, which then influences our next decisions.
- **Nonlinear:** Effect is rarely proportional to cause, and what happens locally in a system (near the current operating point) often does not apply in distant regions (other states of the system). Nonlinearity often arises from basic physics: Bacteria in a river can convert sewage into harmless byproducts, until the sewage load becomes so large that dissolved oxygen is depleted, at which point anaerobic bacteria produce toxic hydrogen sulfide, killing the fish and other organisms.
- **History-dependent:** Many actions are irreversible: You can't unscramble an egg (the second law of thermodynamics). Stocks and flows (accumulations) and long time delays often mean doing and undoing have fundamentally different time constants: During the 50 years of the Cold War arms race the nuclear nations created more than 250 tons of weapons-grade plutonium (^{239}Pu). The half-life of ^{239}Pu is about 24,000 years.
- **Self-organizing:** The dynamics of systems arise spontaneously from their internal structure. Often, small, random perturbations are amplified and molded by the feedback structure, generating patterns in space and time. The stripes on a zebra, the rhythmic contraction of your heart, and persistent cycles in predator-prey populations and the real estate market all emerge spontaneously from the feedbacks among the agents and elements of the system.
- **Adaptive and Evolving:** The capabilities and behaviors of the agents in complex systems change over time. Evolution leads to selection and proliferation of some agents while others become extinct. People adapt in response to experience, learning new ways to achieve their goals in the face of obstacles. Learning is not always beneficial, however, but often superstitious and parochial, maximizing local, short-term objectives at the expense of long-term fitness and well-being.
- **Characterized by trade-offs:** Time delays in feedback channels mean the long-run response of a system to an intervention is often different from its short-run response. Low leverage policies often generate transitory improvement before the problem grows worse, while high leverage policies often cause worse-before-better behavior.
- **Counterintuitive:** In complex systems cause and effect are distant in time and space, while we tend to look for causes near the events we seek to explain. Our attention is drawn to the symptoms of difficulty rather than the underlying cause. High leverage policies are often not obvious.
- **Policy resistant:** The complexity of the systems in which we are embedded overwhelms our ability to understand them. As a result, many seemingly obvious solutions to problems fail or actually worsen the situation.

1. **How much would you need to spend each year to be happy?** That is, how much consumption would be enough to satisfy you?

   Consumption spending here means expenditure to provide for the lifestyle you wish to have, including food, clothing, housing and furnishings, education, health care, travel, entertainment, and all other expenditures on goods and services.

   Consumption does not include charitable giving, but only what you spend on yourself and your immediate family (spouse and children).

   Consumption does not include saving or investment (for example to build future income for retirement, or to leave an estate to your heirs).

   Consumption does not include payment of taxes, but only the cost of the goods and services you purchase.

   One way to think about this is to imagine that you are guaranteed an annuity for life, exempt from income and other taxes, and automatically adjusted for inflation. Under those conditions, what annuity would you require?

   Amount per Year in US$:__________________

   Select one of the following:

   ○ I need at least this much, but more is always better. ○ This much would be enough.

2. **Imagine the following two worlds:**

   World 1: Last year you earned $150,000. This year you earned $200,000.

   World 2: Last year you earned $200,000. This year you earned $150,000.

   The prices of all goods and services are the same in both worlds. The environmental impact of each world is the same, and, through use of green technologies, negligible.

   Which world do you prefer? ○ World 1 ○ World 2

3. **Imagine the following two worlds:**

   World 1: You earn $150,000 per year. Everyone else earns $75,000 per year.

   World 2: You earn $250,000 per year. Everyone else earns $500,000 per year.

   The prices of all goods and services are the same in both worlds. The environmental impact of each world is the same, and, through use of green technologies, negligible.

   Which world do you prefer? ○ World 1 ○ World 2

Table 3. How much is enough?

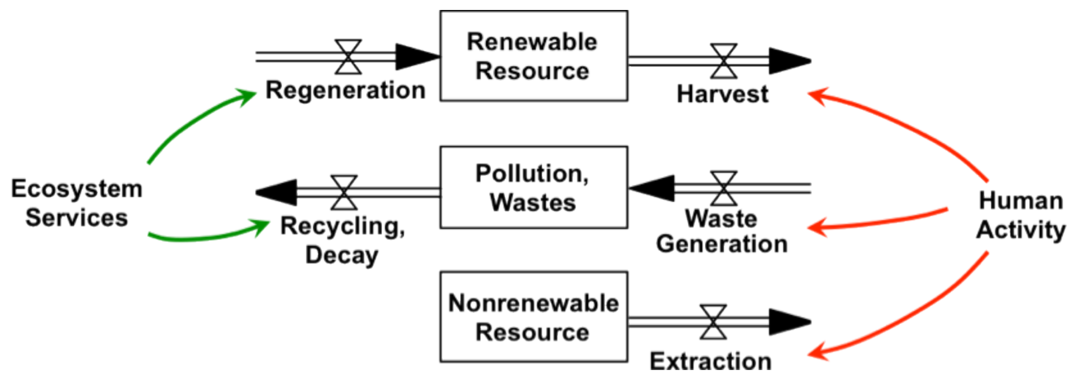


Figure 1. Three necessary conditions for sustainability (Daly 1991) shown in stock and flow notation. Rectangles denote stocks; pipes and valves denote the flows. For example, the stock of renewable resources is depleted by harvest (e.g., logging) and filled by regeneration (e.g., forest regrowth). The harvest of renewables, generation of wastes and extraction of nonrenewables are driven by human activity (the population and economy). Renewable resource regeneration and the processes that render wastes harmless (e.g., breakdown of sewage, removal of CO_2 from the atmosphere) are provided by ecosystem services. For simplicity the stocks that support activities are not shown but are themselves finite: there are no limitless sources and sinks on a finite planet. Additionally, feedbacks from the resource and pollutant stocks to ecosystem services and human activity are not shown.

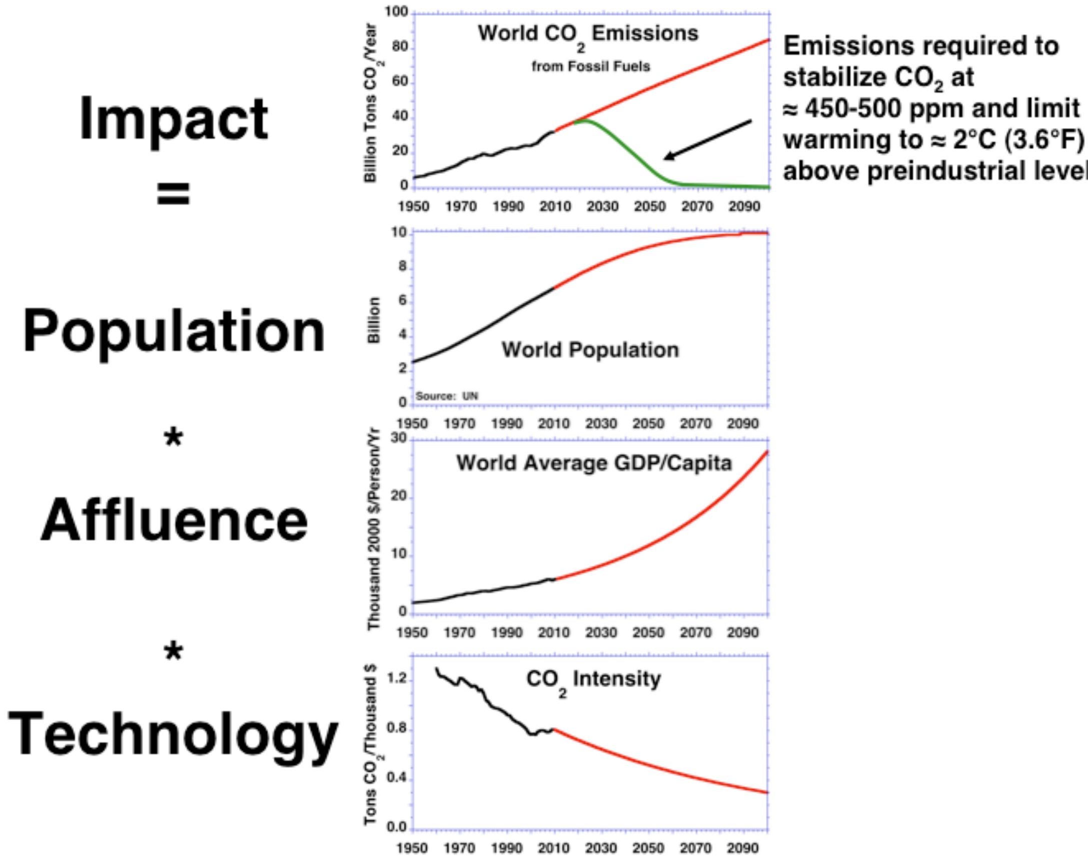


Figure 2. IPAT framework applied to climate change. Black lines: data 1950-2010. Red lines: projections. Population projection: UN Medium fertility variant (2010 revision); GDP per capita and CO_2 intensity of GDP: extrapolation through 2100 of average rate of change, 1950-2010.

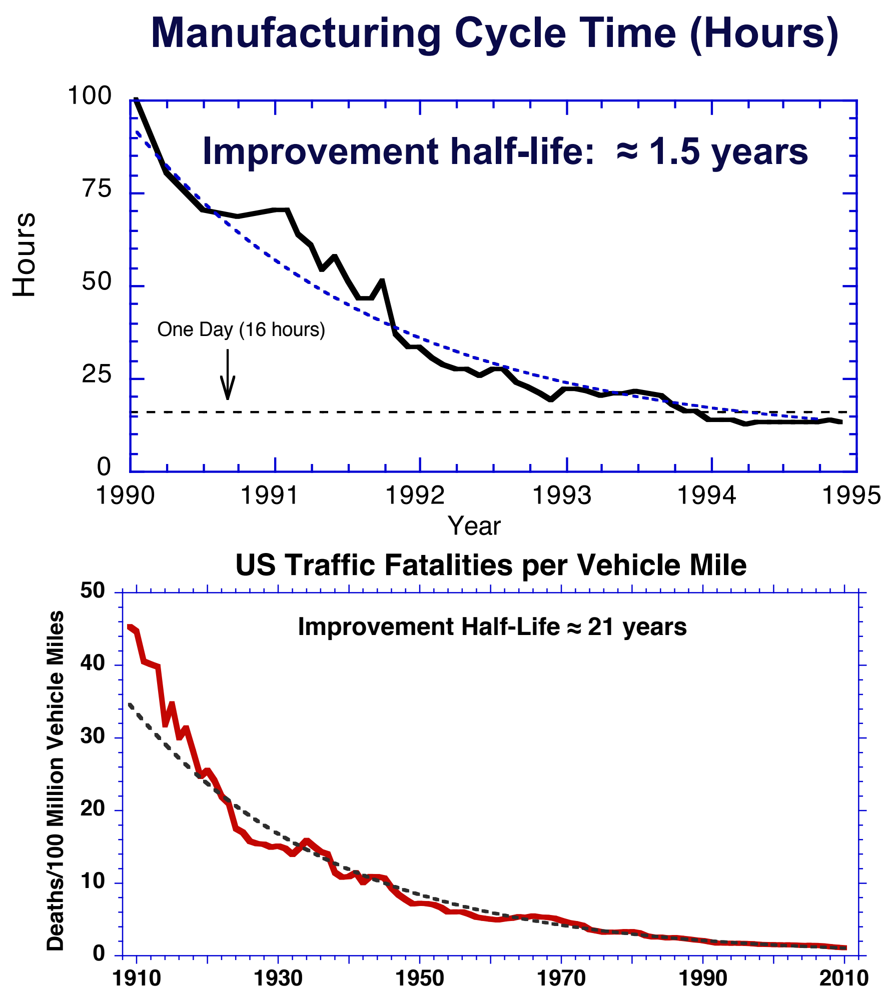
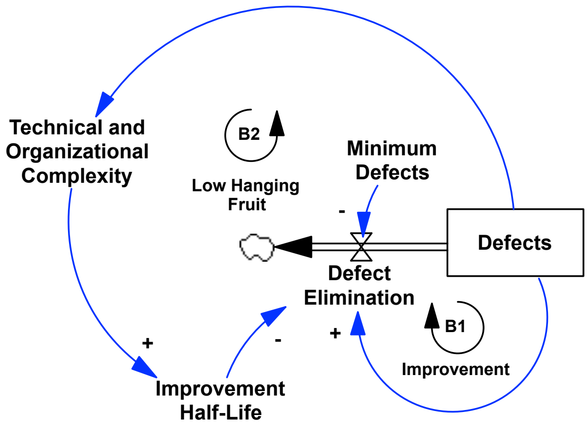


Figure 3. Improvement and improvement half-life in two processes. Top: Manufacturing cycle time in an electronics assembly plant. Bottom: US Traffic fatalities per VMT.



The level of defects generated by any process, D, is governed by

$$dD/dt = \textit{Defect Elimination} = -\phi\,(D - D_{min})$$

where $D_{min} \geq 0$ is the minimum possible defect level. The fractional improvement rate, ϕ, is determined by the improvement half-live, $\phi = \ln(2)/t_h$. If the improvement half-life is constant, the defect level falls exponentially:

$$D_t = D_{min} + (D_0 - D_{min})\exp(-\phi(t - t_0))$$

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 4. Core feedback structure of process improvement.

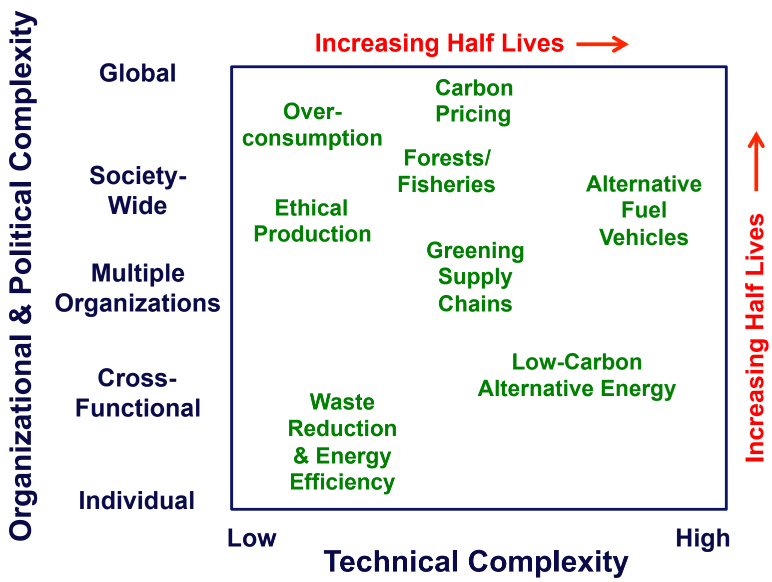
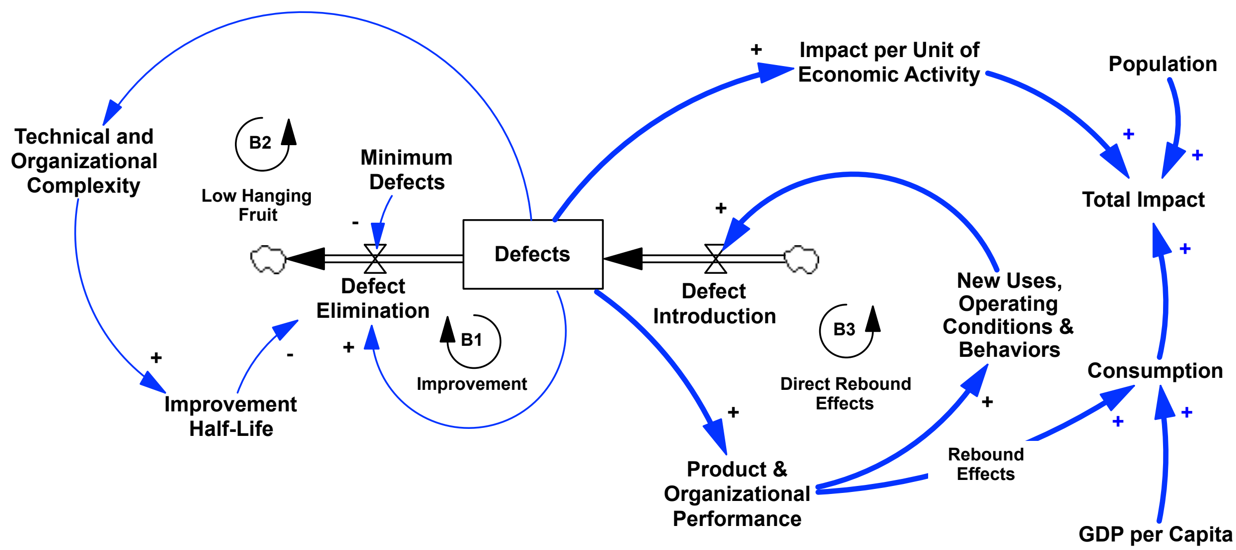


Figure 5. Process improvement half-lives depend on the technical and organizational/political complexity of illustrative sustainability issues.



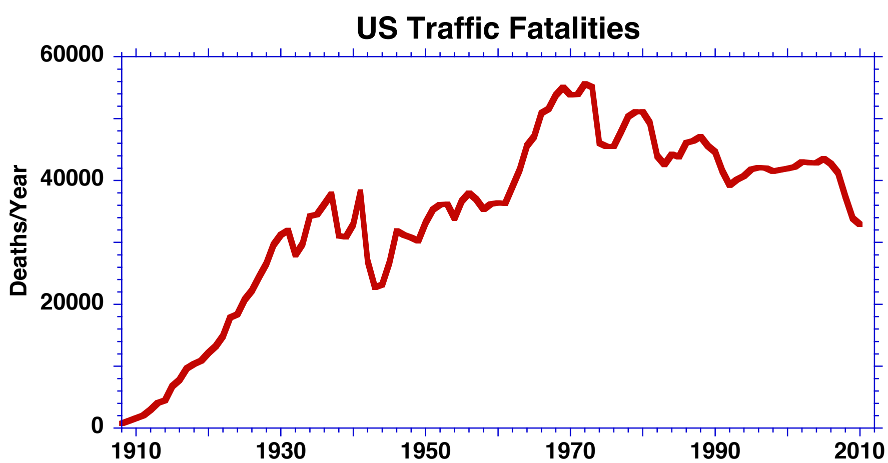


Figure 6. Top: Rebound effects and risk homeostasis offset improvement; better, cheaper products and services increase affluence, which along with population and economic growth, offset lower impact per unit of economic activity created by defect reduction. Bottom: Despite a 40-fold reduction in risk per VMT since 1910, total US auto fatalities per year remain above 30,000 per year.

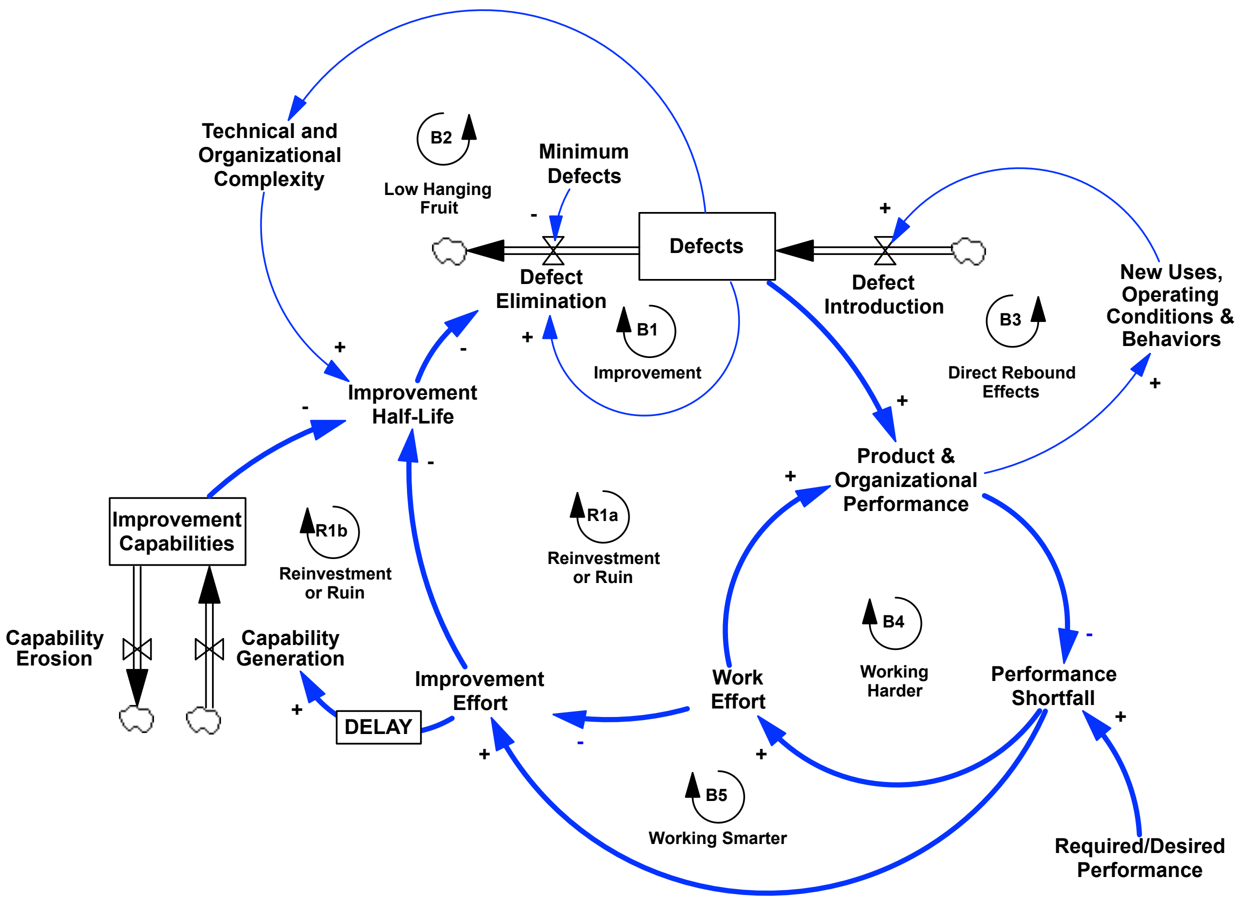


Figure 7. The capability trap: Structure

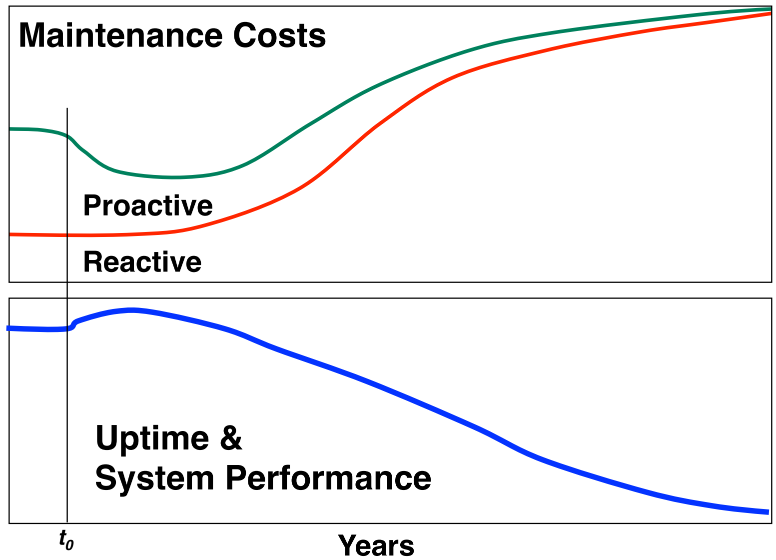


Figure 8. The Capability Trap: Dynamics. Budget cuts at time t_0 force the organization to cut proactive maintenance and improvement activity.

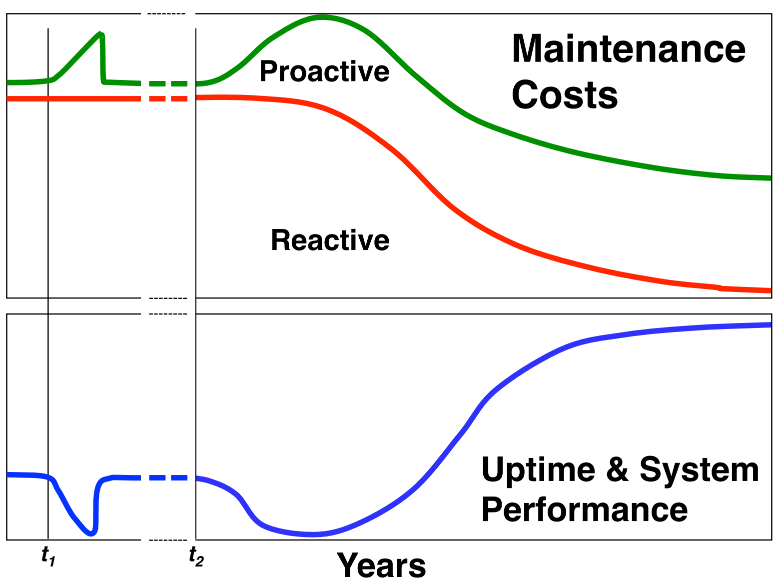


Figure 9. Escaping the Capability Trap: Worse-Before-Better. Improvement effort is given priority at time t_1, but the increase in costs and drop in uptime causes the organization to abandon the effort. If a new effort begins (at time t_2) and is not abandoned, then the initial cost increase and performance drop eventually reverse, leading to lower costs and higher uptime, output, quality, reliability and safety, in a worse-before-better pattern.

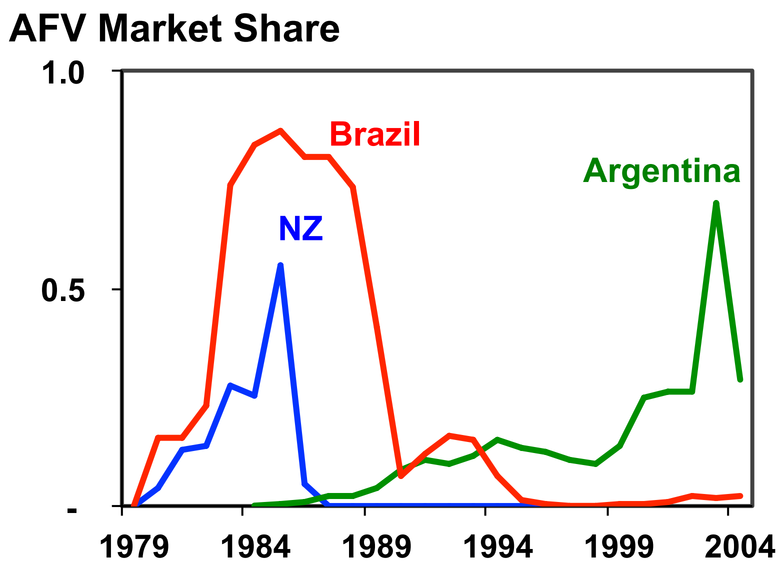


Figure 10. Sizzle and fizzle behavior in the adoption of alternative fuel vehicles (AFVs): Brazil (ethanol); New Zealand and Argentina (CNG).

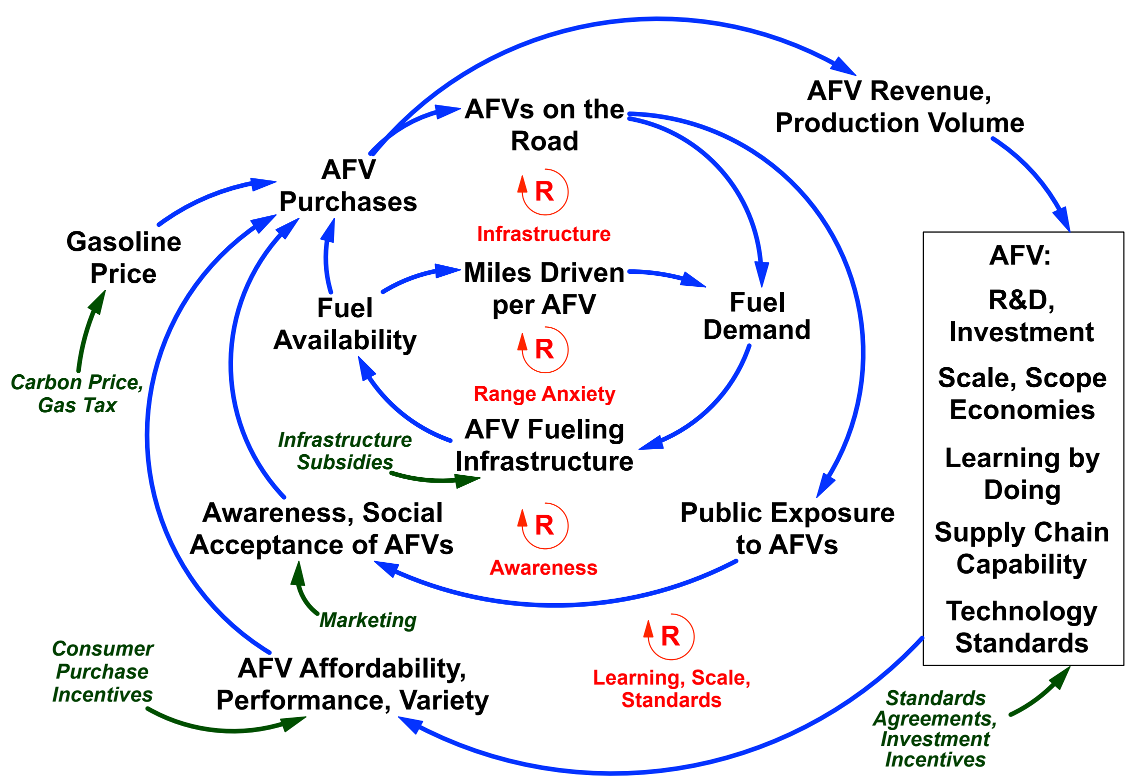


Figure 11. Reinforcing feedbacks conditioning the adoption of Alternative Fuel Vehicles (AFVs).

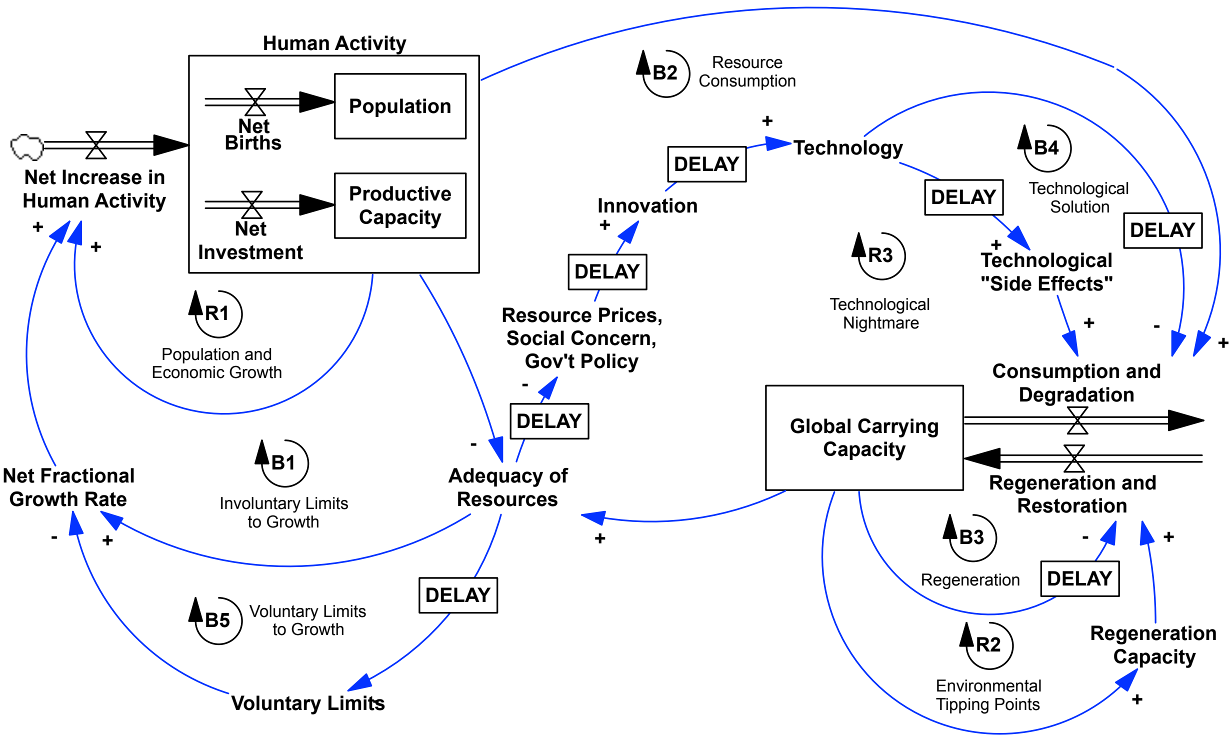


Figure 12. Interactions of growth, carrying capacity and technology

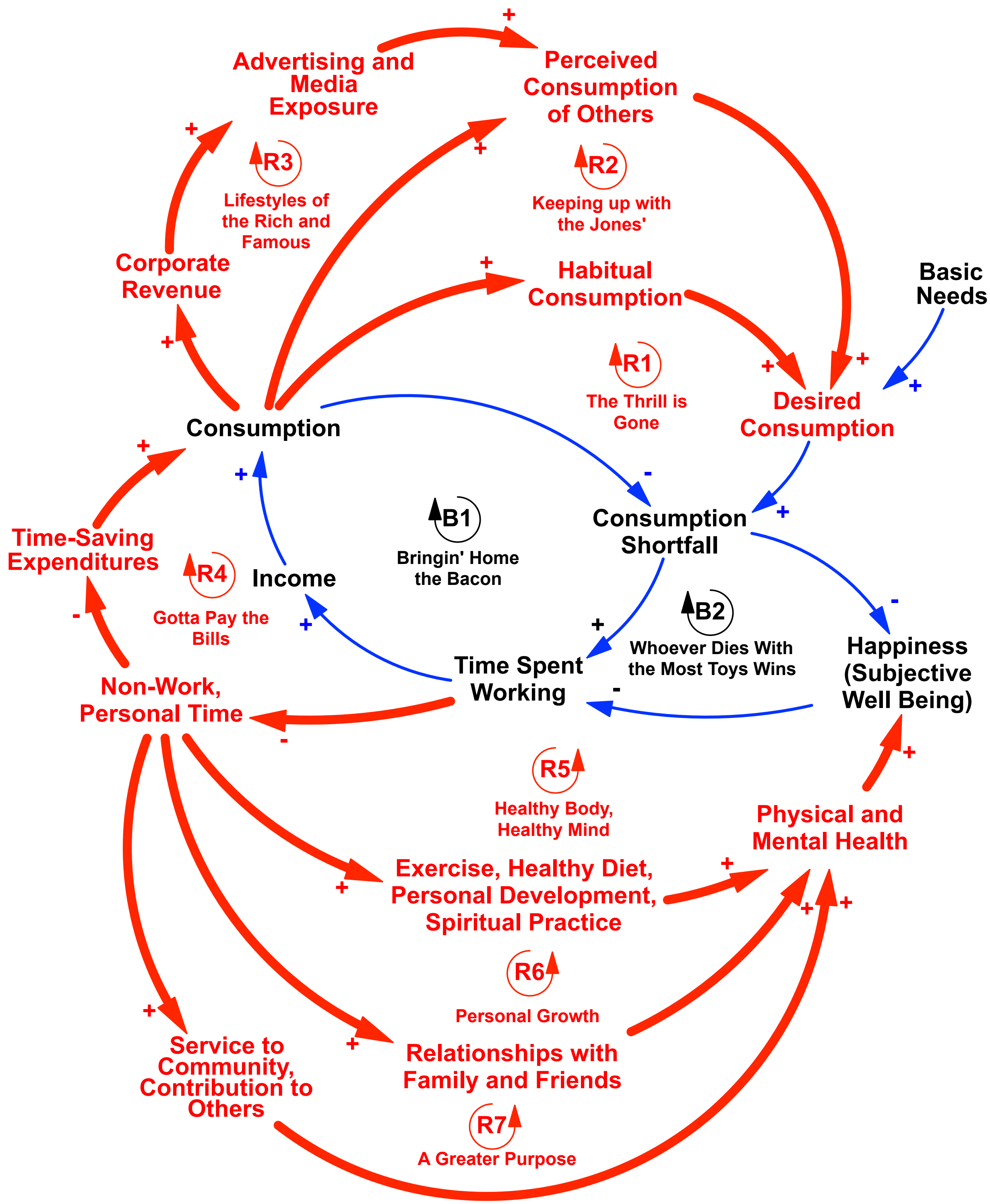


Figure 13. Feedbacks leading to the hedonic treadmill and flat or declining well being despite rising incomes.