[1 Title] Can Innovation Provide a Sustainable Lifestyle?

Joseph A. Tainter

Department of Environment and Society
Utah State University
Logan, Utah USA

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Industrial societies are the products of invention and innovation, and these remain the twin drivers of economic growth.

[2 Vannevar Bush] Near the end of World War II, President Roosevelt asked Vannevar Bush, director of the wartime "Office of Scientific Research and Development," to draft a report on the post-war role of government in promoting science. In his famous report, Bush wrote:

> Advances in science will…bring higher standards of living, will lead to the prevention or cure of diseases, will promote conservation of our limited national resources, and will assure means of defense against aggression.

This statement, so characteristic of our faith in science, became the basis for the emphasis on innovation that we know today, a large enterprise employing many scientists in both the public and private sectors. It is a system that has brought material prosperity in the industrialized countries and high levels of employment.

[3 Chu] Our faith in innovation is undiminished today. Recently Steven Chu, U.S. Secretary of Energy, testified before the U.S. Congress as follows:

> Scientific and technological discovery and innovation are the major engines of increasing productivity and are indispensable to ensuring economic growth, job

creation, and rising incomes for American families in the technologically-driven 21st century.

[4 Innovation and Prosperity] Those of us who live in industrialized nations grew up in this system of innovation, so that we consider it normal. In fact, considered in the long span of human history, our system of innovation is a recent development.

[5 Innovation Past] Our ancestors experienced long periods of no technological change, stretching even to hundreds of thousands of years in the Stone Age. Indeed, in human evolutionary history, it may not have been in our best interest to innovate. Research suggests that humans succeed best, not by innovating, but by copying.

[6 Innovation Now] Yet today we have institutionalized innovation, so much so that we now experience frequent technical changes and product cycles lasting only a few months. A manufacturer that does not innovate cannot compete, and the same observation applies to nations.

[7 Ipad] So accustomed have we become to innovation that we assume it will continue as a matter of routine. Many people expect innovation to produce solutions to the problems we face in energy, climate, and the environment. This assumes that innovation will be as productive in the future as it has been in the recent past. This assumption has received little scrutiny.

[8 Innovation and Sustainability] In particular, our assumptions about innovation are central to our assumptions about what a sustainable future would look like. Let's contrast two views of sustainability and our future:

[9 Diamond] This is the well-known view of Jared Diamond, as well as other environmental writers.

[10 Concepts of Future II] The alternative view, common to conventional economics, is that innovation will invalidate the warnings of Diamond and other environmental writers:

> "No society can escape the general limits of its resources, but no innovative society need accept Malthusian diminishing returns" (Barnett and Morse 1963: 139).

> "All observers of energy seem to agree that various energy alternatives are virtually inexhaustible" (Gordon 1981: 109).

> "By allocation of resources to R&D, we may deny the Malthusian hypothesis and prevent the conclusion of the doomsday models" (Sato and Suzawa 1983: 81).

[11 Conventional Economic Perspective] In the conventional economic perspective, resources are never scarce. They are just priced wrong. Subscribing to what has been called the Principle of Infinite Substitutability, conventional thinkers assume that, provided that markets are undistorted, innovators will respond to price signals and develop solutions to the problems of the day–whether those problems are shortages of energy or other resources, climate change, or merely a need for a competitive product.

[12 Science as Evolving Complex System] The contrary view is that innovation is subject to the evolutionary dynamics of all living systems. That is, it grows in complexity and costliness, and exhausts easy solutions to problems. The productivity of innovation is therefore not constant. Research problems over time grow increasingly complex and difficult to solve. In response, innovation grows increasingly complex, and correspondingly more costly.

[13 Rescher] As described by the philosopher Nicholas Rescheer, research grows more costly not merely in absolute terms, but relatively as well: in the shares of national resources that it requires. Most importantly, as innovation grows complex and costly, it reaches diminishing returns. Higher and higher expenditures produce fewer and fewer innovations per unit of investment. To maintain a constant rate of innovation we must therefore expend ever more resources, and indeed this is what we have been doing.

[14 Contending Possibilities] We have, then two contradictory views of innovation and our future.

Sato and Suzawa:

By allocation of resources to R&D, we may deny the Malthusian hypothesis and prevent the conclusion of the doomsday models" (Sato and Suzawa 1983: 81)

Nicholas Rescher:

> "Once all of the findings at a given state-of-the-art level of investigative technology have been realized, one must move to a more expensive level... In natural science we are involved in a technological arms race: with every 'victory over nature' the difficulty of achieving the breakthroughs which lie ahead is increased" (Rescher 1980: 94, 97).

It is important for planning our future to determine which view is correct.

[15 Evolution of Innovation I] The popular image of science is that of the lone-wolf scholar, an idiosyncratic but persistent genius peering through a microscope or trekking through unexplored jungles. This was indeed how science was conducted through most of the 18th and 19th centuries, the age of naturalists such as Charles Darwin and Gregor Mendel. Yet the naturalists made themselves obsolete as they depleted the stock of general questions that an individual, working alone, could resolve. The principles of gravity, natural selection, and inheritance no longer wait to be revealed.

In every field, early research plucks the lowest fruit: the questions that are least costly to resolve and most broadly useful. As general knowledge is established early in the history of a discipline, that which remains is more specialized. Specialized questions become more costly and difficult to resolve. Research organization moves from isolated scientists who do all aspects of a project, to teams of scientists, technicians, and support staff who require specialized equipment, costly institutions, administrators, and accountants. The size of research teams grows. In research and development, teams are now common. A search on Google.com on the exact term "research team," conducted on 26 September 2010, returned over 9,000,000 internet pages.

[16 Hewlett & Packard]Thus fields of scientific research follow a characteristic developmental pattern, from general to specialized; from wealthy dilettantes and lone-wolf scholars to large teams with staff and supporting institutions; from knowledge that is generalized and widely useful to research that is specialized and narrowly useful; from simple to complex; and from low to high societal costs.

[17 Evolution of Innovation II] As this evolutionary pattern unfolds, the resources and preparation required to innovate increase. In the first few decades of its existence, for example, the United States gave patents primarily to inventors with minimal formal education but much hands-on experience. After the American Civil War (1861-1865), however, as technology grew more complex and capital intensive, patents were given more and more frequently to college-educated individuals. For inventors born between 1820 and 1839, only 8 percent of patents were filed by persons with formal technical qualifications. For the 1860 to 1885 birth cohort, 37 percent of inventors were technically qualified.

[18 Bomber Production] The problem with research that grows complex and costly is that it can produce fewer and fewer outputs per unit of investment. Consider what happens to military technology when it grows complex and costly. In the 1950s-1960s, for example, the U.S. produced

744 B-52 bombers. In the 1980s we produced 100 B-1 bombers. In the 1990s, when the B-2 "stealth" bomber went into production, we were able to afford only 20 of them. This is the result of growth in complexity and costliness.

[19 Augustine's Law] Norman Augustine, an aerospace engineer, called this the "Death Spiral." Carried to its logical conclusion, Augustine suggested:

> In the year 2054, the entire defense budget will purchase just one aircraft. This aircraft will have to be shared by the Air Force and Navy 3-1/2 days each per week except for leap year, when it will be made available to the Marines for the extra day.

However, I did not come here to talk about military technology. I use it only to illustrate how research and development grow complex and costly and reach diminishing returns.

[20 Diminishing Returns to Medicine] If we look at medicine, which is more directly concerned with human well-being, we can see that increasing investments in medical research and application produce diminishing returns in extending healthy lives. We spend more and more to improve general health by smaller and smaller increments. This is why all national health care systems are in trouble.

I have been concerned about this problem for many years–the problem of research and innovation growing so complex and costly that we can no longer afford as much of it as we need. If this is so, then many of our assumptions about the future are incorrect–especially the assumption that innovation will allow us to offset declining resources.

[21 Debbie & José] Recently I met two colleagues–Deborah Strumsky and José Lobo, who had access to databases of U.S. patents that allow us to test whether our investments in research and development have reached diminishing returns. Debbie and José have constructed a database of over

5 million patents. Of these, more than 50% come from non-U.S. entities, so the data reflect the productivity of innovation worldwide.

[22 Pats per Inventor & Size Patenting Teams] Our first result shows that, as expected, the size of teams needed to achieve an innovation has been increasing, having perhaps finally leveled off in the past few years. The growth in size of patenting teams reflects the increasing complexity and difficulty of the research enterprise. Yet while the size of patenting teams grows, the output–measured as patents per inventor–has been declining. Over a period of about 30 years–the length of an average scientist's career–the productivity of innovation has declined by more than 20%.

It is common for older technical fields to become less productive in innovation. This has been known for many decades. We have assumed, though, that this is offset by higher productivity of innovation in newer technical sectors. To investigate whether this is so, we have studied a selection of both older and newer technical sectors.

[23 Surgery, etc.] This figure shows the productivity of innovation in Surgery and Medical Instruments, Metalworking, and Optics. These are older technical sectors in which there are still active programs of research. The chart shows that the productivity of this research is declining.

[24 Drugs, Chemicals, etc.] Similarly, in the sectors of drugs and chemicals–in which there are active research programs–we see a similar program of declining productivity of innovation.

[25 Energy] This chart shows the productivity of innovation in the energy sector. It is one of the most disturbing of our results. Energy is the most important factor in our future, yet in each sector we are experiencing diminishing productivity to innovation. This is the case even in solar and wind technologies, on which we may need someday to rely. It is possible that the solar and wind energy sectors are already technically mature.

[26 Information Tech] Let's look at the newer area of information technology, which has driven our economies for the past 30 years or more. Even though we are continually presented with new electronic products, we can see that the productivity of innovation in these sectors has been declining.

[27 Biotech & Nanotech] The newest technical sectors are biotechnology and nanotechnology. They were recognized by the USPTO only in 1980. In these sectors we would expect to see increasing productivity of innovation. Yet we see just the opposite: From their inception these fields show diminishing productivity in research.

[28 Conclusion I] The productivity of of our system of innovation is declining, and has been for some time. (First noted in 1879.)

[29 Conclusion II] To maintain an acceptable rate of innovation, we will need to allocate more and more resources (money, people) to research and development.

[30 Conclusion III] Within a few years, we will be able to innovate at an acceptable rate only by taking resources from other major sectors—e.g., health care, defense, transportation, infrastructure. This cannot continue forever.

[31 Will Innovation Bring Sustainability?] In the conventional view, as I discussed earlier, it is thought that innovation can always solve problems of resource scarcity. This belief ignores the problems that I have outlined–innovation grows complex and costly, it produces diminishing returns, and it requires increasing shares of our resources.

[32 Future of Innovation] Derek de Solla Price predicted in 1963 that innovation as we practice it now could grow for less than another century. He made that prediction nearly 50 years ago.

[33 Solving Problems of Sustainability] Innovation will not disappear overnight. We will continue to have innovations for the foreseeable future. But innovation will continue to decline in productivity over the next several decades. By current trends, in another generation innovation will have lost nearly 50% of its productivity. Industries and nations will begin to realize that it is no longer productive to invest in innovation. One hopeful sign is that innovation in lower-cost products has shifted to emerging nations.

[34 Innovation, Emerging Nations] The good news is that emerging nations still have much potential to innovate. Their costs of research are lower, and their companies can profit from simple innovations that are not profitable in industrialized nations. Soon the emerging nations will be major players in worldwide innovation. But in time emerging nations will also experience increasing complexity and costliness in research, and declining productivity. This outcome is inherent in the research process.

[35 Innovate Forever?] And if this conclusion is wrong and we can innovate forever, what kind of world will we have?

[36 Steady State] Based on this discussion, we can foresee that the age of innovation as we have known it will be a passing phase of human history. It will not last forever. Many people count on innovation to offset declining resources per person in our future. But if energy per person will not increase, and if innovation continues to become less productive, the engines of economic growth will disappear. The result would then be an economy that does not grow—a steady-state economy, as envisioned by the pioneering economist Herman Daly.

Steady-state means exactly that: Consumption is flat. Employment is level. Throughputs of matter and energy are fixed. Birth rates equal death rates. Savings and investment precisely equal depreciation. This is also sometimes known as full-world economics. It has been anticipated by philosophers since the 18th century, and explicitly formulated in the 19th century by John Stuart Mill: “The end of growth leads to a stationary state.”

I am not advocating a steady-state economy, merely noting that the laws of physics and the complexity of innovation may force one upon us. Indeed I have serious reservations about what a steady-state economy would mean for the earth’s peoples. Whatever uncertainties any of us may have about a steady-state economy, we must all begin to consider that this may be our future. As journalists, you have an important role to play in such a discussion.