# Presidential Address: Innovation in retrospect and prospect

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*Abstract*. This paper asks whether innovation has slowed in recent decades. While there has been dramatic progress in information and communications technology, the recent record of innovation in the crucially important agriculture, energy, transportation, and health care sectors is cause for concern. The paper also considers whether the pace of innovation is sufficient to improve or even maintain living standards in the face of still rapidly growing population, global warming, and other challenges. I review the major market failures that lead to under-provision of innovation and question whether current innovation policy, particularly patent policy, is effective in promoting innovation. JEL classification: O3, Q2

*Innovation: rétrospectivement et prospectivement.* Ce mémoire se demande si l'innovation a ralenti au cours des dernières décennies. Alors qu'il y a eu progrès dramatique dans les technologies de l'information et des communications, le dossier des innovations récentes dans des secteurs aussi importants que l'agriculture, l'énergie, le transport et la santé a de quoi nous donner du souci. Le texte se demande aussi quel rythme d'innovation pourrait suffire pour améliorer ou maintenir notre niveau de vie face à une population qui croît rapidement, aux changements climatiques, et aux autres défis. On passe en revue les principales faillites du marché qui ont pu engendrer une offre insuffisante d'innovation, et on se demande si la politique d'innovation, en particulier pour ce qui est de la politique des brevets, est efficace pour promouvoir l'innovation.

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## 1. Introduction

There is little doubt that technological innovation is the most important economic force underlying improvement in the human condition and that more inputs are being provided to the innovation process than ever before. However, innovation also depends on using those inputs effectively, on exogenous events (including good luck) and on the physical and biological constraints of the world around us. Merely increasing inputs devoted to innovation as time passes is not sufficient to ensure increasing or even stable rates of innovation, and there is no guarantee that the rapid pace of innovation we have experienced in the twentieth century will continue. Concerned observers such as Huebner (2005) have questioned whether the pace of innovation might actually be declining.

This essay provides a brief overview of the recent (and not so recent) pattern of innovation and considers what we can expect from innovation as we move forward in the twenty-first century. Despite the dramatic innovations in information and communications technology (ICT) over the past few decades, I suggest that innovation has slowed markedly in many areas. In this paper I focus on agriculture, energy, transportation, and health care.

Agriculture and health care are obvious choices for investigation. Obtaining food, now done primarily through agriculture, has been the dominant economic activity of human beings for almost our entire history and remains a major economic activity in much of the world. Health outcomes, particularly life expectancy, are fundamentally important and are normally taken as key indicators of well-being. Energy and transportation are also economically important sectors that are closely connected to the daily life and well-being of most people. Furthermore, they have been associated with major technological innovation in the past century. In addition, while these four industries are of great importance in themselves, I would also argue that the pattern of innovation is similar in other major industries such as manufacturing and construction.

I see little prospect of a revival of rapid technological progress in these areas. Such concerns raise the question of whether technological innovation will be sufficient to lead to continued improvement in living conditions through the twenty-first century in the face of various problems confronting the human race.

This slowdown in innovation might simply be the result of some sort of diminishing returns in the innovation process. In addition, however, it is quite possible that the market failures that tend to generate under-provision of innovation are becoming increasingly important. This paper reviews the major market failures affecting innovation and considers the current state of policies targeted at these market failures. I consider the role of patent policy in some detail and address the concern that current patent policy imposes significant frictions on the innovation process. I also consider possible policy changes that might improve the chances of generating sufficient innovation to deal effectively with the major challenges of the twenty-first century.

Most of the paper is devoted to innovation and its consequences at a global or worldwide level. However, I also pay some specific attention to the pattern of innovation in Canada and the United States. Section 2 provides a brief overview of the history of innovation, while section 3 contains comments on definitions, measurement, and theories of innovation. Sections 4, 5, 6, and 7 address the recent record of innovation in the major sectors of concern: agriculture, energy, transportation, and health care. Section 8 reviews the major market failures that tend to reduce the rate of innovation below the efficient level, and section 9 considers the role of patent policy in addressing such market failures. Section 10 offers concluding remarks.

## 2. The long run

Modern human beings (*Homo sapiens*) are thought to have emerged as a species about 200,000 years ago.[1] For the first 95% of our tenure on the planet so far, we *Homo sapiens* survived as hunter-gatherers. English philosopher Thomas Hobbes (1651) famously observed that humans in their natural state lived lives that were 'nasty, brutish, and short' – and this is often taken as a reasonable description of the life of a typical hunter-gatherer. While there has been some dissent from this view, there is little doubt that hunter-gatherer populations generally lived at the Malthusian limit (i.e., on the margin of subsistence) with average life expectancy of less than 25 years at birth and perhaps 35 years for those fortunate enough to survive the first few years of childhood.[2]

The hunter-gatherer lifestyle of *Homo sapiens* was supported by technology in the form of fire and crude stone tools, both of which were inherited from earlier humans and were therefore already in use 200,000 years ago. The rate of technological progress during the *Homo sapiens* hunter-gatherer period was very slow. For most of this period, if a typical hunter-gatherer were transported forward or backward in time 100 years or 1,000 years, or even 10,000 years from his or her actual lifetime, little if any difference would be observed in the state of technology, life expectancy, or real living standards. Climate changes and evolutionary changes in the human genome probably had a greater and more rapid impact on living conditions than technological progress over this period.

The first great technological innovation in the history of homo sapiens was the first agricultural revolution, which began a mere 10,000 to 12,000 years ago,[3] as human beings began to plant and harvest crops and to raise domestic animals.

1 There is less than complete agreement on the timing of major transitions in human evolution. For a useful overview I would recommend the Smithsonian Museum of Natural History human origins website at humanorigins.si.edu.

2 These estimates are based in part on recently observed hunter-gatherer populations. See, for example, Gurven and Kaplan (2007).

3 The first agricultural revolution is also called the Neolithic ('new stone age') revolution. There are several later historical periods also sometimes called agricultural revolutions.

Over the subsequent few thousand years innovations such as writing, the wheel, and the use of bronze and iron tools had a transformative effect on much of the world, allowing for the development of true civilizations. Even so, technological change would have seemed almost imperceptibly slow to a typical individual.

Furthermore, for the first 95% of the 11,000 or so years since the agricultural revolution, the vast majority of world's population continued to live at the margin of subsistence with only small improvements in life expectancy and living standards. Agriculture did, however, allow for a dramatic increase in population density and hence in overall population and allowed for a small privileged class that was able to pursue objectives other than just day-to-day subsistence.

One of the pursuits followed by the privileged few was intellectual enquiry, which gave rise to what many view as the second great innovation in the history of our species – the scientific revolution – often dated as beginning in 1543.[4] This revolution consisted primarily of the application of the scientific method (broadly defined) to major areas of human interest. It ultimately (although not immediately) allowed most of the human population to get significantly beyond the Malthusian limit. Average life expectancy for the world as a whole is now between two and three times that of hunter-gatherer populations, and real incomes for most of the world's population are far beyond mere subsistence levels.

During the last few centuries, human beings have become accustomed to observing remarkable changes in technology over the course of their lifetimes. At no time has this been more true than during the past century. Many of us are amazed by how recent innovations such as iPods and Blackberrys have changed our lives. And we can barely imagine life without technologies such as electric lights, motor vehicles, and refrigeration, all of which have become generally available only within the past hundred years.[5]

There is a large literature on the history of technological innovation, including an entire journal titled *History and Technology*. I make no pretence of providing a review of this extensive literature here. However, within economics, highly influential treatments of the history of technological innovation include Rosenberg (1986) and Mokyr (2003). I would also recommend the discussion of innovation in the classic work of North and Thomas (1973) on the 'rise of the western world.'

Most of the literature on the history of innovation has a strongly optimistic tone, focusing on the accelerating pace of innovation in the centuries following the start of the scientific revolution. The scientific revolution provided an enormous boost to innovation. However, sooner or later we are likely to experience diminishing returns in technological innovation. Perhaps that time is upon us.

4 This date is the publication date of the famous work by Nicolaus Copernicus on planetary motion. The scientific revolution was part of the broad cultural movement referred to as the Renassaince.

5 The electric light was invented by Thomas Edison in 1879, patented in 1880. The first modern car is credited to Karl Benz in 1885, patented in 1886, and the modern refrigerator is credited to Carl von Linde in 1876, patented in 1877. These inventions did not come into general use until the early twentieth century.

Will we now have a harder time making significant progress? The tremendous progress of the past few decades in information and communications technology has perhaps distracted us from the slowdown in the rate of progress in other areas.

## 3. Conceptual issues

The online *Oxford Dictionary* defines an innovation as 'a new method, idea, product, etc.' The term 'etc.' in the definition covers a lot of possibilities, but we are focusing here on innovations related to technology – to the way in which goods and services are produced and to the nature of those goods and services. An innovation might be an idea or scientific discovery that contributes to technology, it might be a better way of organizing production, or it might in itself be a useful new product.

The dictionary definition just given implies that the primary characteristic of innovation is simply newness and that an innovation can be good, bad, or neutral. However, following Schumpeter (1934), it is common in economics to define an innovation as a *successful* new method, idea or product. I follow that practice here. It has the advantage that we can refer just to 'innovations' instead of having to refer repeatedly to 'successful innovations.'

The relevant measure of success for assessing innovation in our context is the ability to contribute to human living standards or well-being. This is somewhat broader than focusing just on changes in total factor productivity or something similar as a measure of innovation. I will not seek to define a single numerical index for innovation performance but will rely on a range of both quantitative and qualitative indicators.

The simplest theory of innovation is what I think of as the comic book theory – because I remember seeing a comic in which Isaac Newton was hit on the head by an apple in the first panel, leading to the development of Newtonian physics and to the Industrial Revolution in subsequent panels. In the comic book model innovation is driven mainly by chance and by intellectual curiosity. There is also a sociological view, attributed particularly to Max Weber, relating innovation and other aspects of capitalism to the cultural and religious context.[6] An important contribution of economists to the theory of the innovation, including particularly Hicks (1934), North and Thomas (1973), and Rosenberg (1986), among others, has been to emphasize the role of price signals, property rights, and economic incentives more broadly in inducing innovation A helpful textbook treatment of the theory (and practice) of innovation is Scotchmer (2004).

Innovation is, of course, affected by chance, by sociological context, by prices, by inputs to the innovation process, and by other factors as well. In this essay I do

6 Weber's basic thesis is outlined in the famous book *The Protestant Ethic and the Spirit of Capitalism*, completed in 1905 (in German) and first translated into English in 1930.

not take a position on the relative importance of different sources of innovation or on the most suitable specific theory of innovation. The primary question of this paper relates to the recent record of innovation, whatever the cause of that record. However, in considering appropriate policy toward innovation, I focus on those aspects of innovation that can be influenced by policy variables.

## 4. Agriculture

Prior to the first agricultural revolution, food acquisition (hunting and gathering) occupied almost all of a society's available labour effort. Even after the agricultural revolution, obtaining food was, until recently, by far the dominant economic activity in all regions of the world, although activities such as religion, the military, and a small commercial sector also absorbed a noticeable fraction of the labour force. Nowadays, in high-income countries like Canada, agriculture is only a small direct contributor to economic activity. At present, agriculture accounts for approximately 2% of Canada's GDP and a similar share of the labour force, down from about 40% of the labour force as recently as 100 years ago.[7]

For Canada, a slowing of productivity growth in agriculture would not have major negative effects, given its relatively small contribution to GDP. For the world as a whole agriculture accounts for about 6% of GDP but about 37% of the labour force.[8] These numbers reflect the fact that in much of world, especially in Africa and South Asia, subsistence and near-subsistence agriculture remain very important. Such areas are highly vulnerable to any slowdown in agricultural productivity growth, given their rapidly rising populations.

Technological progress in food production peaked during what is often called the 'green revolution,' which occurred, roughly speaking, in the third quarter of the twentieth century.[9] The most important aspect of the green revolution was the development of improved crop varieties. The three other major factors were innovations in irrigation, fertilizers, and pesticides. Improved machinery and agricultural education also contributed.

Figure 1 provides an overview of improvements in agricultural productivity. It shows the annualized growth rate in yield (output per hectare under cultivation) from 1961 through 2008 for the world's major crops. The unit of measurement is physical output. The crops shown here, accounting for about half of all calories

7 Data on GDP shares and labour force shares is readily available from Statistics Canada at www.statcan.gc.ca. The full food production sector, including processing, distribution, and retailing, along with basic agriculture, now accounts for about 8% of GDP.

8 This data is taken from the online CIA fact book at www.cia.gov/library/publications/the-world-factbook/geos/xx.html accessed in July 2010 and applies to 2007.

9 The green revolution is typically taken to have begun about 1943 or 1944 and to have lasted until the late 1970s. Some observers include the last quarter of the twentieth century as well, dividing the green revolution into two periods – early and late, in which case it would be the early period in which most technological progress occurred.

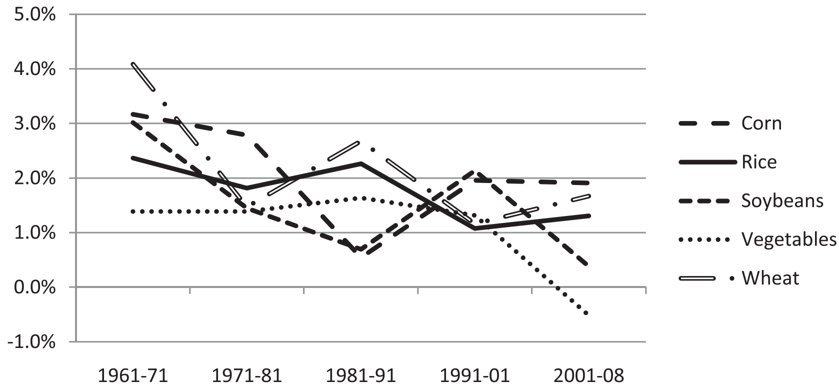


FIGURE 1 Annualized crop yield growth rates, 1961–2008
SOURCE: Food and Agriculture Organization (FAO), United Nations, 2010

consumed by humans[10], include the most important crops in the human diet: rice, wheat, and corn (or maize), all of which are in the cereal family. Soybeans and vegetables are also important and illustrate other major crop families. This group of products is representative of food production as a whole.

The pattern of technological progress is clear. Early in the green revolution, yield growth rates were high, but they have fallen significantly (by more than 50%) since the end of the 1960s. The mere fact that yield growth rates are still generally positive indicates that output per hectare is still increasing, but world population is also increasing. If land under cultivation remains relatively stable, then yields must grow by a rate equal to the rate of growth of population in order to keep output per capita stable.

At present the world population growth rate is about 1.1% per year,[11] and average growth in the yield of major crops is of similar magnitude. However, there are at least two other important factors reducing per capita availability of food. One such factor is the diversion of corn and other crops to ethanol production for fuel.

The other important factor is the overall availability of agricultural land. Total output rose even more rapidly than yield during the green revolution because the total area under cultivation increased. However, by the early twenty-first century, relatively little productive new land was available for cultivation. For the all-important cereal family, there was actually slightly less land under cultivation in 2008 than in 1981. Factors such as soil erosion, rising sea levels, and expansion of urban areas reduce land availability. If food supply problems intensify and

10 Calorie consumption can be obtained from the FAO food balance tables at faostat.fao.org. Other major sources of calories include sugar (8%), meat products (8%), and dairy products (7%).

11 A standard reference for world demographic information is the *United Nations World Population Prospects*. The 2008 version is the most recent release currently available.

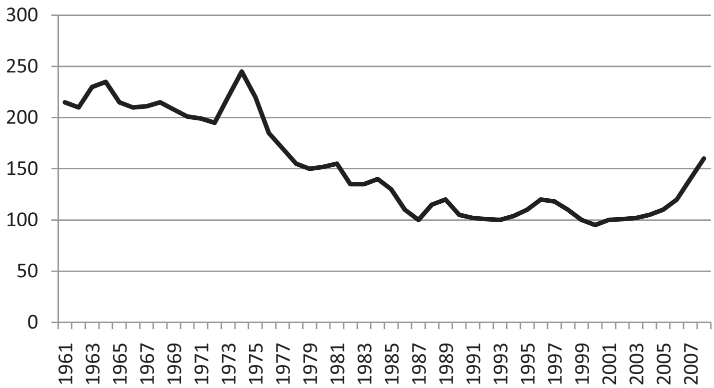


FIGURE 2 Extended Annual FAO Real Food Price Index
SOURCE: FAO, 1998–2000 = 100

food prices rise, we might expect additional land to be converted from other uses, partially offsetting the factors tending to reduce land availability. However, new agricultural land comes at increasingly high opportunity cost. We might also expect some induced innovation as food prices rise, but the increased prices needed to create such incentives imply increased hardship, especially for those already malnourished or close to that state.

The FAO estimates that just over 1 billion people were 'undernourished' as of 2009 – about 15% of the world's population.[12] This is a significant increase in both absolute numbers and share of population relative to the previous assessment in 2006. Much of the undernourishment is concentrated in sub-Saharan Africa and South Asia. If yield growth continues to fall, more widespread malnutrition and more frequent localized famines are likely outcomes.

The recent turnaround in the relative availability of food has already generated significant food price increases. Figure 2 provides an overview of food price changes since 1961, showing the FAO real food price index from 1961 through 2008. Figure 2 shows that there is significant year-to-year volatility in food prices but the overall trend is very clear. Generally speaking, prices fell from 1961 through to the end of the twentieth century. Since the turn of the twenty-first century food prices have been rising and reached a 30-year high in 2008. If real prices rise further in coming decades, obtaining a healthy diet will move beyond the reach of an increasing fraction of the world's population.

It is not difficult to understand why yield growth has slowed. First, the development of new crop varieties has slowed since its golden age of the 1950s and 1960s, despite the development of genetic modification. One friction is the considerable political opposition and genuine scientific concern associated with genetically modified crops. Second, during the 1960s there was dramatic

12 This is obtained from the FAO website http://www.fao.org/hunger/en/, accessed in June 2010.

expansion of irrigation. It is now difficult to expand irrigation, as most of the likely irrigation projects have been built and there is a growing relative scarcity of fresh water.[13] Pesticides were also a major source of productivity growth during the green revolution, but many pest control technologies cause environmental contamination or other problems. There is little prospect of pesticides' providing additional productivity growth in the near future. Similarly, there is not much scope for additional productivity gains from expanded use of fertilizers.

Perhaps the most important source of increases in agricultural productivity since the 1970s (i.e., after the green revolution) has been economic in nature – the replacement of command systems for agricultural production by market-based systems, particularly in China. The result was a large improvement in yield for the affected countries. Indeed, a significant part of the world's increase in rice yields in the 1980s was due to China, following its initial market-based reforms beginning in 1978. However, the gains from market-based reforms are essentially one-time gains that have now been realized as almost all of the former communist world has made the transition from central planning to markets.

In the fishing industry wild fish stocks are being depleted, but there has been an enormous increase in aquaculture (fish farming). Now close to 50% of the world's seafood comes from aquaculture. There are many concerns associated with aquaculture. The industry is replete with (mostly negative) externalities, as aquaculture has significant negative ecological effects. However, there is considerable potential for aquaculture to be an increasingly efficient and important source of protein and calories for human consumption.

The other main area of food production relates to meat, dairy products, and eggs. Considering this part of the food industry does not change the overall picture. There is little prospect of innovation in this area that would provide significant ongoing improvements in productivity. Furthermore, innovation is not the only thing that affects yields. Declining relative availability of water, soil depletion, global warming, and other factors put downward pressure on yields. Without agricultural innovation, yield growth would probably be negative (as it was for vegetables in the most recent decade).

Agricultural innovation has fallen markedly since the green revolution. Of course, by the later years of the green revolution (in the 1970s) food surplus was often considered a greater problem than food scarcity. Large stockpiles of food accumulated in storage facilities, particularly in Europe and North America. Low agricultural prices were viewed as a 'problem' by many governments through the 1980s and 1990s, with attendant pressures in countries like Canada to subsidize farmers to compensate for low prices.

It seems likely that this (relatively) happy period of agricultural surplus arising from rapid technological progress has ended. I am not predicting widespread

13 It is possible to use desalinization of salt water as a source of water for irrigation, but this is a costly technology, primarily because of high energy demands. It therefore requires high food prices to be economically feasible.

famine any time soon, but I would predict an increasingly challenging problem of generating sufficient productivity gains in food production to feed the world's growing population in the face of major threats to the food supply system, including global warming.

Slowing innovation in agriculture is important but is only part of the story underlying current problems of malnutrition. Enough food is still produced for the earth's entire current population to have a healthy diet. However, in many countries, a combination of low income, high fertility rates, faulty political institutions, poorly functioning markets, and political, ethnic, and religious conflict often prevents healthy diets from being achieved.

## 5. Energy

Energy accountis for about 7% of GDP in Canada,[14] slightly more than for the world as a whole. As with agriculture, this percentage understates the full importance of the sector, as energy is an important input to many other productive activities and generates substantial consumer surplus.

When I began graduate school in 1975, energy was a major topic of both academic and popular discussion, mainly because of the actions of the Organization of the Petroleum Exporting Countries (OPEC) in dramatically raising oil prices in the 1973–74 period. It was easy to discern two schools of thought on energy. One school of thought was articulated by Meadows, Meadows, and Randers (1972) in *The Limits to Growth*. The basic thesis was that the world economy was on a path to 'collapse' over a relatively short period of time, owing in part to the problem that we would run short on petroleum and other non-renewable resources.

The other school of thought was the more optimistic 'innovation' school, which held that we would switch from fossil fuels (coal, natural gas, and petroleum) to alternative clean energy sources, particularly wind and solar power. Such a transition would require technological innovation in these alternative energy areas, but there was hope that by 2010 our dependence on fossil fuels might be a distant memory.

To give a sense of the optimistic predictions, here are three such examples taken from Bezdek and Wendling (2002). In 1979 the Harvard Business School Energy Project predicted that solar and wind power together would provide annual energy contributions to the U.S. economy of approximately 5 quadrillion (5,000 trillion) British Thermal Units (BTUs). A 1980 report from the prestigious National Research Council predicted 4.1 quadrillion BTUs annually by 2000, and a 1981 Department of Energy (DOE) report predicted a much more modest annual contribution of 1.8 quadrillion BTUs by 2000.

14 http://www.nrcan-rncan.gc.ca/stat/index-eng.php#fig1.

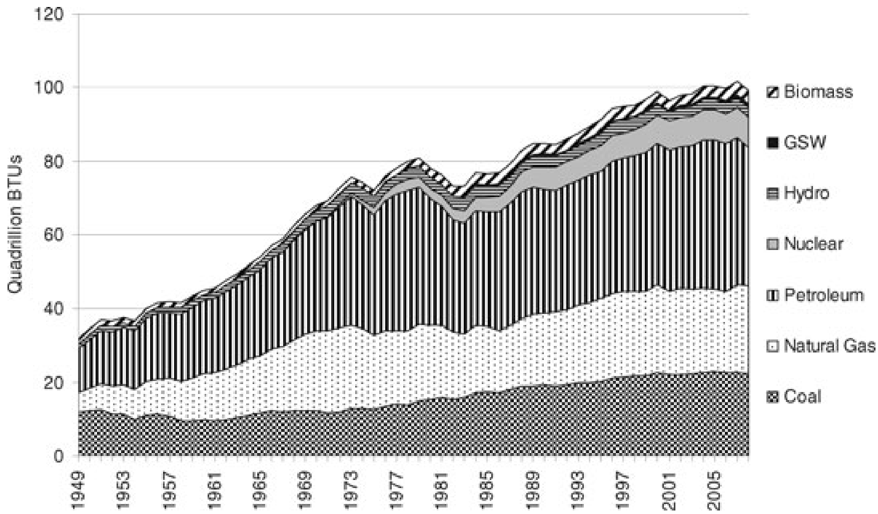


FIGURE 3 Sources of US Energy: 1949–2008
SOURCE: US Energy Information Administration

These three forecasts were provided by highly reputable forecasters. However, in this case they were off the mark. The actual contribution of solar and wind energy in 2000 was 0.1 quadrillion BTUs. Thus the 'conservative' estimate in this group was off by a factor of almost 20, while the other forecasts were off by factors of 40 to 50. Figure 3 shows the evolution of sources of U.S. energy supply from 1949 through 2008. (Early data for the world as a whole are less readily available, but the recent pattern is very similar to the U.S. pattern.)

Fossils fuels accounted for virtually all of the U.S. energy supply in 1949. By the 1970s, other sources, particularly nuclear and hydroelectric power, were making noticeable contributions, but over 90% of the supply was still based on fossil fuels. There has been little change since then, apart from some expansion of nuclear power, most of which occurred in the 1980s. The category GSW stands for 'Geothermal, Solar, and Wind.' This category is almost too small to be visible to the naked eye on the graph, appearing as a fairly heavy boundary between biomass and hydro.

The share of renewable energy in the world energy mix was almost unchanged between 1980 and 2006. Nuclear power came on line in significant quantities in the 1980s, but since about 1990 the shares of renewable, nuclear, and fossil fuel energy sources have been almost constant. The much publicized expansions in biomass, solar, and wind energy did nothing more than keep pace with increases in traditional and nuclear energy in the overall energy mix.

Both the energy optimists and the energy pessimists from the 1970s were wrong. The optimists grossly overestimated the role of innovation in renewable energy. Nevertheless, innovation in renewable energy might have had a meaningful impact despite a low market share. For example, a backstop technology such as wind power might limit the market power of fossil fuel suppliers and thus contribute to lower energy prices. However any such effect is of little comfort to those who hoped that alternative energy would have largely displaced fossil fuels by now.

The pessimists greatly overestimated the speed with which we would 'run out' of conventional non-renewable energy sources. We are not about to 'run out' of fossil fuels in the immediate future. As of 1980, proven oil reserves were about 667 billion barrels[15] and annual consumption was about 22 billion barrels, suggesting that the world had proven reserves equal to about a 30 year supply. Since then, new discoveries of reserves have exceeded consumption. As of 2008, proven reserves were about 1.3 trillion barrels and annual consumption was about 30 billion barrels, suggesting that the world had proven reserves equal to about a 40-year supply. For natural gas proven reserves represent about a 70-year supply at current consumption levels.

We should not assume that the depletion of fossil fuels can be ignored. Additions to reserves through new discoveries are in increasingly costly and risky locations, and, sooner or later, such reserves will become uneconomic to exploit. However, the time horizon for dramatic reductions in fossil fuel supply due to depletion probably takes us beyond the twenty-first century.

### *5.1. Energy innovation*

Assessing the importance of innovations is not easy, but various lists of top innovations have been developed. The value of such lists should not be exaggerated, but they do contain some meaningful information. One of the most credible lists of this type is the 'Top 20 Engineering Achievements of the Twentieth Century' as assessed the (U.S.) National Academy of Engineering.[16]

The top item on the list is 'electrification' – the development of electricity generation and transmission networks that allow for the conversion of basic sources of energy (such as water power, natural gas, and coal) into electric power and the distribution of electric power to homes and businesses. This development, which occurred mainly in the first part of the twentieth century, has completely transformed our lives, allowing for the technology we rely on virtually every waking moment of our lives – electric lights, modern appliances, computers, and so on.

Only two other energy-related innovations appear on the list: oil and gas technologies at number 17 and nuclear technologies at 19. Oil and gas technologies

15 This information is from the British Petroleum *Statistical Review of World Energy*, June 2009. It can be found online at http://www.bp.com/statisticalreview.

16 See www.greatachievements.org.

TABLE 1
*Forbes Magazine* (2009) top 10 innovations of the past 30 years

| | |
|---|---|
| 1. | The Internet |
| 2. | Personal and laptop computers |
| 3. | Mobile phones |
| 4. | E-mail |
| 5. | DNA testing and sequencing/human genome mapping |
| 6. | Magnetic resonance imaging (MRI) |
| 7. | Microprocessors |
| 8. | Fibre optics |
| 9. | Office software (spreadsheets, word processors) |
| 10. | Non-invasive laser/robotic surgery (laparoscopy) |

play a role in electricity generation, but are also used for home heating, motor vehicles, and in other areas. These uses were developed in the nineteenth century but did not become widespread until the early twentieth century. Nuclear power, used mainly to generate electricity, was developed in the 1940s and 1950s.

It is these three technologies – conventional generation and transmission of electricity, oil and gas technologies, and nuclear power – that dominate the energy sector, and these technologies are not new. There has been incremental innovation in these areas in the latter third of the twentieth century, but the rate of innovation has been much more limited than in the previous hundred years.

*Forbes Magazine* recently created a list of the top 30 innovations of the last 30 years (1979–2009). The top 10 items are shown in table 1. These innovations are concentrated in information and communications technology (ICT). None is associated with energy. There are three energy-related innovations further down on the list, photovoltaic cells at 18, large-scale wind turbines at 19, and developments in biomass fuels at 25. While these developments are significant contributions, figure 3 indicates that, to a first approximation, they are yet to have a noticeable impact on the pattern of energy use.

There are also recent innovations related to fossil fuels. One such innovation is improved underwater extraction technology, allowing more aggressive offshore activity. However, this innovation is not looking so impressive after the disastrous spill off the U.S. Gulf Coastthat began in April 2010.[17] Related innovations include improved exploration methods and extraction technologies for tar sands and oil shale and various improvements in natural gas technology.

The energy sector was completely transformed in the 100 years between 1860 and 1960, which dramatically improved the standard of living in most of the world in the process. The pace of innovation in the energy sector slowed markedly after 1960. Possibly major new technologies are on the horizon, such as hydrogen-based fuel cells, but their development has been slow.

17 The spill followed an April 2010 explosion on the British Petroleum rig Deepwater Horizon.

There is another major concern about the energy sector – negative externalities, particularly global warming. As is now widely accepted, use of fossil fuels generates emissions of greenhouse gases that insulate the earth and contribute to global warming.[18] The major reason we are concerned about innovation in energy and are so hopeful regarding alternatives to fossil fuels is not really that we are worried about running out of fossil fuels in the near future. A greater concern is that continued fossil fuels use will cause potentially catastrophic global warming.

Apart from concerns about global warming, the consequences of slowing innovation seem less of a problem in energy than in agriculture. One reason is that back-up technologies already exist and will be used as the real price of energy rises. In particular, wind could be much more extensively used and is not far from being economic at current energy prices. Some countries, such as Denmark,[19] already obtain significant amounts of energy from wind. Solar energy is not as close to being economic for general electricity generation as wind, but is potentially very useful in some situations. Nuclear generation of electricity can also be expanded, although waste storage issues and other safety issues remain a concern.

Also, energy use (unlike food consumption) could be sharply reduced without significantly affecting quality of life. For example, good technology exists for dramatically improved fuel efficiency for motor vehicles and for much more efficient use of energy in buildings. At current prices most users do not find such changes worthwhile, but if energy scarcity causes prices to rise significantly, such adjustments should be relatively easy and should not seriously jeopardize overall living standards.

### *5.2. Global warming*

As for global climate change, the hope that innovation will create a clean, low-cost source of energy that will displace fossil fuels seems unlikely to be realized. The real problem with fossil fuels is that they are underpriced in light of the negative externalities they cause. Appropriate taxes would raise the price of energy and would spur innovation in alternative energy sources.

There is an enormous literature on global climate change that I cannot do justice to here. There is no doubt that some warming has occurred,[20] with associated changes in rainfall, wind patterns, and various other climate variables.

18 The relationship between fossil fuel emissions and global warming remains an issue of heated political debate and significant scientific uncertainty. There is little credible disagreement regarding the existence of such a relationship, buts its precise nature and impact remain difficult to assess. A well-respected source on such issues is the United Nations Intergovernmental Panel on Climate Change (IPCC). See www.ipcc.ch.

19 A 2006 report from the Danish Energy Authority reported that wind provided 20% of Danish electricity production at that time and outlined a plan to increase that figure to 50% by 2025.

20 As I write, I note that the National Oceanic and Atmospheric Administration (www.noa.gov) reports that June 2010 was the warmest June on record – the fourth month out of six so far in 2010 to have such a distinction in what is so far the warmest year on record.

However, while the changes create challenges, they have not had a first-order effect on quality of life so far.

One very serious consequence of global warming is likely to be an increase in the sea level caused by melting of ice sheets in polar regions and in Greenland. Over the twentieth century the sea level rose by an average of about 20 cm (8 inches). Projections for sea-level increases over the twenty-first century vary widely. The UN environmental program (UNEP) yearbook describes the range of scientific opinion. The 2009 edition reports a range of reasonable projections for the average increase ranging from about 20 cm at the low end and to about 150 cm (1.5 m) at the high end. This increase would vary dramatically across locations, with sea level rising much more in some places than others.[21]

A 1 m average rise in sea level would, according to UNEP, displace more than 100 million people at current population levels – and undoubtedly many more when population growth is accounted for. However, this is less than 2% of total world population. Relocation of people and economic activity would require only slow adjustment – just gradual pressure to expand activity on higher ground. While this would be a major problem in some areas, it is not likely to significantly affect average living standards for the world as a whole through the twenty-first century.

Nevertheless, metaphorically at least, the twenty-first century is only the tip of the iceberg. If the Greenland ice sheet were to melt completely, this would raise the sea level by a catastrophic 7 m (23 ft). The time horizon for such melting is expected to be perhaps several hundred years and a lot can happen in such a time period. Global warming might even be offset by factors that have a cooling effect. Still, at this stage, while rising sea level will be primarily a localized problem in the twenty-first century, it appears likely to be major global problem in the twenty-second century.

## 6. Transportation

The Academy of Engineering list of the most important engineering accomplishments of the twentieth century had electrification at the top. The next two items on the list were the automobile and aircraft – both from the transportation sector. These innovations completely transformed transportation in the first part of the twentieth century.

Karl Benz is often thought to be the most important pioneer in the development of the modern automobile.[22] He built a working motor vehicle in 1885 and slowly began limited commercial production. By 1899 there were several

21 Variations occur in part because melting is concentrated in just a few places, and in part because of a complex array of geophysical factors that are only partially understood.

22 Benz's first vehicle was a tricycle design with three wheels. Gottlieb Daimler is credited with the first four-wheel automobile in 1886. A reliable reference on automobile history is the U.S. Library of Congress website at www.loc.gov/rr/scitech/mysteries/auto.html.

companies producing motor vehicles, the largest of which was the Benz company, which was producing a few hundred cars per year. Mass production of automobiles as an innovation is credited to Henry Ford, who designed and produced the first Model-T Ford in 1908 and began his first automobile assembly line in Detroit in 1914, selling more than 250,000 cars that year, roughly a thousand-fold increase over the production of Benz only 15 years earlier.

The desire to fly has been an aspiration of human beings for a very long time, and many lighter-than-air craft and gliders have been flown over the centuries. However, the first powered flight by a heavier-than-air craft was the famous 1903 flight by Orville Wright near Kitty Hawk, North Carolina. (His brother, Wilbur, flew later that day.)

One hundred years ago, in 1910, only a tiny fraction of the world's population had even seen a car or powered aircraft, let alone used one. Even in wealthy countries such as Canada and the United States the idea that an ordinary person might actually use a car or aircraft for routine transportation would have seemed more like science fiction than any plausible reality.

A mere 50 years later, by 1960, the automobile was ubiquitous in countries such as the United States and Canada and was a major contributor to popular culture. Movies, songs, and novels featuring cars were common, an entire new sport (car racing) had developed, and drive-in or drive-through restaurants had become an important feature of the urban landscape. Air travel had become a standard activity for business people and for vacation travellers by 1960. Commercial jet aircraft had been in use for a number of years at that point, and plans were in place for human space flight (the first of which took place in 1961).

The period from 1910 to 1960 was a period of revolutionary innovation in transportation. By comparison, not much happened in the subsequent 50 years. Motor vehicles improved after 1960, but only slightly, albeit with improved fuel efficiency. Classic cars from the 1950s and before are much prized and, to a first approximation, are similar to currently produced vehicles.

Similarly, there have been only modest improvements in air transport. As with motor vehicles, the 50-year period from 1910 to 1960 was a period of major qualitative change for aircraft, while the subsequent 50 years have been a period of only incremental innovation, apart from the space program, whose major contributions were in the 1960s. Since then, however, the space program has declined in relative importance and is now a relatively minor activity.

Considering the rest of the transport sector does not alter the picture. There has been some improvement in and expansion of high-speed rail in the past few decades, but, overall, rail transport has not changed much since the early part of the twentieth century or before, as is also true of shipping. Urban rapid transit has been expanded but, from a technological point of view, it is similar to what it was in 1960.

The slowdown of innovation in transportation is not in itself a major problem. Transportation services are an important sector (accounting for about 6%

of GDP in Canada) and they are not in any particular jeopardy. Nevertheless, whereas transportation improvements were a major contributing factor to increasing quality of life in the first part of the twentieth century, transportation improvement is not likely to contribute to enhanced living standards in the medium-term future.

By some measures, transportation might even be an increasing friction on quality of life. For example, the Statistics Canada *General Social Survey on Time Use* indicates that commuting times in Canada have been rising. Data are limited, but the survey has been done on an occasional basis since 1992, most recently in 2005. The average Canadian commute time rose from 54 minutes in 1992 to 59 minutes in 1998 and to 63 minutes in 2005. While this is not a striking change, it should be treated as a subtraction from real income and illustrates the general point that transportation improvements are not currently a significant positive force for living standards.

It has been suggested that advances in communications technology might substitute for transportation – allowing workers to stay home and connect to a 'virtual office' through the Internet and other communication channels. While there is significant 'virtual' economic activity of this type, the impact on transportation appears to be negligible so far. See, for example, Choo, Mokhtarian, and Salomon (2005), who estimate that telecommuting has reduced travel in the United States by less than 1% relative to what it would otherwise be, and aggregate distance travelled continues to trend upwards. Still, we cannot rule out significantly increased telecommuting in the future.

## 7. Health care

The last sector to consider is health care, often taken as one of the two main sectors (along with food) for assessing quality of life. Perhaps the most fundamental health outcome is simple survival – most people want to survive as long as they can, subject to maintaining reasonable health. Therefore, life expectancy is a very important measure of health outcomes. Figure 4 shows the evolution of life expectancy at birth in Canada from 1921 through 2006. Canadian life expectancy at birth (shown by the solid line in figure 4) increased dramatically from about age 57 in 1921 to about 81 in 2006. Women and men show a similar pattern over time (not illustrated in the diagram), with women consistently outliving men, although the gap has declined in recent years and is now about 4.6 years.

In 1921 a person in his or her late fifties would have been considered old and would expect to be in declining health. Nowadays such a person is still in middle age and can reasonably look forward to not just years but decades (perhaps two or three) of additional life. Furthermore, we are not only living longer but we are healthier while we are alive. In the years since 1920 we have probably added

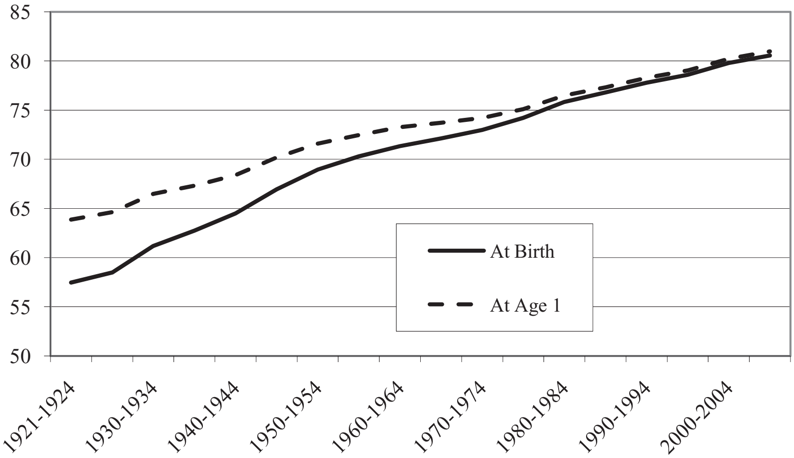


FIGURE 4 Canadian life expectancy, 1921–2006
SOURCE: Statistics Canada

25 years of healthy life for a typical Canadian. This has had an enormous positive impact on any reasonable estimate of lifetime well-being.

However, figure 4 shows that increases in life expectancy are now coming much more slowly than they did in the first half of the twentieth century. For example, in the 20-year period from 1930 to 1950 life expectancy increased by more than a full decade, from 60.3 to 70.6. In the most recent 20-period in the data, from 1986 though 2006, life expectancy increased by only 3.1 years, less than one-third as much. A close look at the data indicates that since about 1960 the rate of progress has been fairly stable, although these gains have been achieved by the application of dramatic increases in the resources devoted to health care and to health research.

Much of the gain in life expectancy at birth has come from reductions in infant mortality (deaths in the first year of life). In the early 1920s infant mortality was about 10%, while at present it is about 0.5%. As infant mortality cannot be reduced below zero, there is not much chance of significant further improvement. If we abstract from infant morality gains by looking at life expectancy at age 1 (shown by the dashed line in figure 4), we see a more muted pattern of concavity, but concavity is still present, indicating a decline in the rate of improvement.

In 1900 doctors played only a modest role in overall public health. They could set broken bones, stitch wounds, and perform some other useful surgical procedures. They understood sterilization and had access to a few useful medications. However, relatively few people experienced any direct benefits from medical interventions. The increases in life expectancy and general health of the nineteenth century[23] are thought to have arisen mainly as a result of rising per capita incomes with the attendant improvements in diet, sanitation, and accommodation, rather than because of medical innovations. In contrast, much of the dramatic gain in health in the twentieth century is due to medical innovations. It is likely that almost everyone reading this article has significantly benefited from modern health care.

Nevertheless, a diagram like figure 4 almost suggests that we might be approaching some sort of asymptote. Such a possibility seems consistent with data on the very oldest humans. Even though average life expectancy has risen steadily (although increasingly slowly) in recent decades, the age of the very oldest people has increased little if at all. At present the oldest documented living person is 114, the same age as in 1985 and little different from the age of the oldest person at earlier points in the twentieth century. It is as if there is some upper limit on longevity that is very hard to change, given our current understanding of biology. Possibly, however, genetic manipulation could potentially break through this barrier.

It is possible to identify major innovations and check on when they occurred. After reviewing many lists of major medical advances, I suggest five sets of innovations that are always at or near the top of any list: vaccines, anti-infective medicines (including antibiotics), other medicines, medical imaging (x-rays, etc.), and surgical innovations.

### *7.1. Vaccines*

The idea that exposure to an infected person might prevent later disease has been known for many centuries. However, this is a dangerous practice, as the exposed person is quite likely to contract a serious and sometimes fatal case of the disease. The innovation of the vaccination principle is to expose patients to a relatively safe agent that will provide immunity against a more serious threat. For example, most modern anti-viral vaccines are based on inert (non-reproductive) forms of the underlying virus. The immune system generates antibodies and ‘remembers’ the antibody template generated to fight the vaccine and is then much more likely to be able to prevent infection by the live virus.

The first scientific use of the vaccination principle was due to Edward Jenner in 1796, who used cowpox to vaccinate humans in the hope it would keep them from getting smallpox, which it did. Cowpox was similar enough to smallpox to confer immunity but not similar enough to be a major risk to human health. Smallpox had been one of the world’s leading causes of death up to that time.[24] Owing to smallpox vaccinations, the disease was ultimately eradicated entirely,

23 It is hard to estimate changes in life expectancy over the nineteenth century. However, it seems likely that Canadian life expectancy rose from perhaps about 40 in 1800 to about 50 by 1900. See Riley (2005).

24 Mortality estimates for smallpox are uncertain and controversial. However, it is plausible to suggest that smallpox killed more than 30% of the population when it first entered the Americas-similar to its effect on other populations at first contact with the disease. In the

TABLE 2
Start of major vaccination programs

| | | | |
|---|---|---|---|
| 1778 | Smallpox | 1935 | Yellow Fever |
| 1885 | Rabies | 1955 | Polio |
| 1897 | Plague | 1963 | Measles |
| 1917 | Typhoid | 1967 | Mumps |
| 1923 | Diphtheria | 1969 | Rubella |
| 1926 | Pertussis | 1982 | Hepatitis B |
| 1927 | Tuberculosis | 1983 | Pneumonia |
| 1927 | Tetanus | | |

although not until the twentieth century. Jenner was 'lucky' that a suitable vaccine for smallpox (the cowpox virus) existed in nature. Most other successful vaccines required the ability to create inert versions of the infective agent and therefore did not emerge until late in the nineteenth century. Table 2 shows when major vaccination programs were introduced. (Other successful but less significant vaccines have also been developed.)

The major era of vaccine innovation was the first half of the twentieth century. The diseases in question, such as Typhoid, Diphtheria, Pertussis (Whooping Cough), and Tuberculosis, had been major scourges of the human species for centuries or longer. The diseases appearing after 1960 on the list, while serious, were less significant sources of human mortality.

Developing vaccines against recent viral threats has proven very difficult. The most well-known example is the HIV virus that causes AIDS. One problem is that HIV, as a retrovirus, compromises the body's immune system. In addition the virus itself evolves quite rapidly, so a vaccine against one variant may not be effective against other variants. Rapid evolution is also a problem with flu viruses. Every year new strains of the flu are identified, and modified flu vaccines are manufactured. However, there is a significant likelihood that a highly virulent flu could cause high levels of mortality, as the so-called Spanish flu did in 1919.[25]

### *7.2. Anti-infective medicines*

Perhaps the second great medical innovation of the twentieth century was anti-infective medicines. Unlike vaccines, which prepare the immune system to fight off pathogens, anti-infectives attack the pathogen directly and are normally administered simultaneously with or after exposure to the pathogen. Most attention is

extreme of the previously isolated Easter Island, smallpox killed 90% of the population within a few years of first being introduced. See Brander and Taylor (1998).

25 See the Nature Web Focus at www.nature.com/nature/focus/1918flu/. The 'Spanish' flu killed over 20 million people and probably many more, and is thought to have sickened about 1 billion, approximately half of the world's then population. It mutated from an avian flu and is related to the H1N1 virus. Its origins are not entirely clear, but it did not originate in Spain. It is now thought likely to have originated in either the United States or China.

focused on antibiotics, which are used against bacteria. There are also anti-viral, anti-fungal, and anti-parasitic medicines. The first widely used antibiotics were sulpha drugs, whose medical properties were discovered in the 1930s, followed by penicillin,[26] which was first used commercially in the early 1940s. Research in antibiotics moved forward quickly, and new variants of the penicillin class of antibiotics were developed, along with new classes of antibiotics, such as cephalosporins and tetracyclines, in the 1940s.

At first, antibiotics seemed like miracle drugs. They would quickly and easily cure patients suffering from a wide range of serious ailments, including bacterial pneumonia, tuberculosis (TB), scarlet fever, rheumatic fever, and major sexually transmitted diseases. Antibiotics also sharply reduced infection rates for people suffering from wounds or undergoing surgery. However, within a relatively short period of time, certainly by the end of the 1950s, doctors began noticing some changes. It was taking longer and requiring larger doses of antibiotics to cure many infections than was the case a decade earlier. And some diseases successfully treated with the first wave of antibiotics seemed to need newer antibiotics to resolve them.

It was soon realized that bacteria were evolving. Treatment by an antibiotic might quickly kill off almost all TB bacteria inhabiting the lungs of a particular person, but one bacterium out of a million might have some slight genetic idiosyncrasy giving it more resistance to the drug being used. That bacterium would be the one to survive and reproduce and possibly be transmitted to other people. The resistant bacteria would spread and this Darwinian process would continue, generating progressively tougher bacteria. This process was accelerated by the common practice of over-using antibiotics, including taking them for colds or other diseases for which they are ineffective and incorporating them in animal feed.

By the 1970s the problem had changed from simply finding a suitable antibiotic for a given bacterial pathogen to continually finding new antibiotics to stay ahead of the evolving bacteria. However, as of the 1970s, pharmaceutical research was still extending its lead. I can recall young medical researchers in the 1970s saying that infectious disease research was a field to avoid on the grounds that little was left to do – that the infectious disease problem was almost solved.

Since the 1980s the infectious disease outlook has become less positive. Increasingly tough antibiotic-resistant bacteria have emerged, including bacteria that cause many secondary infections in hospitals and nursing homes and also including bacteria causing tuberculosis, pneumonia, and various sexually transmitted diseases. Progress on anti-viral medicines has been slow. For example, while progress has been made in controlling the effects of HIV, a cure is not

26 Alexander Fleming is normally regarded as the leading pioneer in antibiotics. In 1928 he found that a bacterium he was trying to grow had its growth inhibited by a penicillium mould that had accidentally contaminated the dish in which the bacterium was being cultured. The active ingredient in the mould, later named penicillin, was isolated in the early 1940s, a little after sulpha drugs became available.

in sight. Also, the most important parasitic infection, malaria, which kills well over a million people every year, now has strains that are resistant to the major anti-malarial medications.

Innovation has continued to occur in anti-infectives since the 1980s, but much more slowly than in the 1930s and 1940s. A realistic assessment would suggest that we have actually lost ground since 1980 in the war against infection, although anti-infective medicines remain an enormous net boon to human beings compared with the situation before their discovery.

### *7.3. Other major medical innovations*

The world's top five drugs (by revenue) in 2009 were Lipitor (for cholesterol), Plavix (for cardiovascular problems), Nexium (for ulcers), Advair (for asthma), and Seroquel (for psychiatric problems).[27] Other important drugs effectively address medical issues such as high blood pressure, diabetes, thyroid deficiencies, pain, depression, sexual function, and other areas of concern. Most readers of this article will benefit significantly by using some of these medications as they age. Many people in their sixties, seventies, and eighties can now live active and satisfying lives instead of being severely limited by chronic health problems. Most of the drugs referred to here are recent innovations. Thus, any general decline in the rate of innovation in medication outside the anti-infective area is less than obvious. Nevertheless, some observers, such as Cuatrecasas (2006), suggest that the 'pipeline' for new drugs is much less promising than in the recent past.

Imaging, sometimes referred to as radiology, began shortly after the discovery of the x-ray in 1895.[28] Within a decade x-rays were being widely used for medical purposes. Important extensions of imaging technology have followed, including fluoroscopes, computed tomography (CT) scans, ultrasound, magnetic resonance imagery (MRI), and nuclear medicine (e.g., positron emission tomography (PET)). Early versions of these technologies were crude but improved markedly over time. All of these technologies have been in use since the 1970s or before, although they continue to be improved.

Surgery is medical treatment based on physical operations, often to remove or repair damaged tissue or organs. Surgery is probably the oldest type of medical intervention. The very first known human writings – cuneiform writing from the Sumerian culture in Mesopotamia from about 4,000 years ago – contain fairly sophisticated material about surgery. Surgery has advanced primarily through small evolutionary steps right up to the present. Perhaps the single most important innovation was Lister's pioneering use of sterilization in 1865.[29]

27 Drug sales data by revenue and by the number of prescriptions is available from IMS Health.

28 German physics professor Wilhelm Röntgen is credited with discovering x-rays in 1895. Others had encountered them previously but had not investigated them. He wrote up his initial findings and had his paper published in a journal 50 days later, showing that we have gone backwards in some ways since then. He received the first Nobel Prize in Physics (1901) for this discovery.

29 In 1865 Henry Lister, a professor of surgery at the University of Glasgow, read about the recent work of Louis Pasteur showing the role of microbes in causing disease and in spoiling food.

Important twentieth-century innovations in surgery include pure improvements in technique and have also arisen from innovations in related areas, such as anaesthetics, imaging, and lasers (which are often better than cutting tools for removing tissue). Assessing the impact of surgical interventions is not easy. Careful assessments of life-years gained, such as Unal et al. (2005) suggest that since 1980 the contribution of surgical gains has been positive but modest.

There is no clear reason to suggest that the rate of medical innovation differs markedly from the life expectancy changes shown in figure 4. Few medical breakthroughs in the past 30 or 40 years can compare (in impact) with the innovations of the late nineteenth and early twentieth centuries.

Figure 4 is based on Canadian data, although the pattern in other high-income countries is similar. In low-income countries, on the other hand, gains in life expectancy have been much more muted. The issue in such countries is not a failure of innovation but a failure to successfully transfer known technology to the local environment, combined with a simple lack of resources to devote to health care.

Possibly we are on the verge of another major medical breakthrough. Manipulation of human genes, in particular, has been suggested as a technology with potentially enormous consequences that might dwarf even vaccines and antibiotics in importance. For now, however, we are living in an age of marginal improvement rather than major leaps forward.

## 8. Innovation and market failure

The previous sections suggest that the pace of innovation in important areas has slowed dramatically, and that improved innovation is required if humanity is to maintain or improve living standards in the face of major emerging challenges over the twenty-first century. I would suggest further that significant pro-innovation policy changes are called for.

At present we already have a significant amount of pro-innovation policy in place. However, my assessment is that the policies in place are no longer doing an adequate job of addressing the underlying market failures they are targeted towards. There are three major market failures that, in the absence of corrective policy, would lead to an undersupply of innovative activity.

### *8.1. Incomplete property rights*

Perhaps the best known of these market failures is a form of incomplete property rights – the difficulty an innovator has in appropriating the benefits arising from

Suspecting microbes as a cause of post-operative infection, Lister started simple antiseptic procedures for surgical patients. Surgery was risky at that time – a last resort. Lister's mortality rate for invasive surgery dropped from about 45% to 15% after he implemented antiseptic procedures, making surgery a realistic alternative for many more patients.

an innovation. This argument was first formalized by Nelson (1959) and Arrow (1962). Most important, a successful innovation can often be copied by others – essentially a free rider problem that reduces the returns to the innovator and correspondingly reduces the incentive to innovate.

Also, part of the appropriability problem is due to externalities. Even if an innovation is not copied directly, creating the innovation often generates knowledge that helps the innovation efforts of others. (Early efforts to estimate this externality are reviewed by Griliches 1992.) Both the imitation problem and R&D externalities imply that private markets would tend to underprovide innovation relative to the efficient outcome.[30]

### *8.2. Informational asymmetry*

A second market failure affecting innovation is informational asymmetry as described, for example, in Amit, Brander, and Zott (1998). An innovator developing a new product typically has a better idea about the prospects for success than do potential investors. Furthermore, innovators have incentives to overstate the likelihood of successful product development, potentially leading to adverse selection, where the market for innovation finance is dominated by relatively low-quality innovations. Potential investors understand the problem and might therefore be reluctant to provide finance. In addition, investors cannot readily monitor the effort provided and other actions of innovators, leading to a market failure of the 'agency' type. These problems can arise in any investment environment, but they are particularly acute in financing innovation.

### *8.3. Intertemporal market failure*

The third market failure I wish to emphasize is not as well understood as the first two but is important in this context. This market failure is sometimes called *intergenerational* or *intertemporal* market failure and is due to the inability of different generations to transact with one another through markets.

The possibility of intertemporal market failure is implicit in the fundamental work of Arrow (1951) and Debreu (1959) on the first theorem of welfare economics showing that an undistorted competitive economy with complete markets achieves pareto efficiency. The earliest work by Arrow on the first theorem was entirely static. The entire economy took place at a moment in time. However, Debreu and others were able to extend the result to a world with many periods. This extension simply requires interpreting goods as being indexed by time. Thus, for example, in order to be confident that outcomes will be pareto efficient in an

30 There are forces that might lead to excessive investment in innovation, including R&D races, where different firms might duplicate each others' activities in an effort to win a race to obtain a patent or make an important discovery. See, for example, Reinganum (1985). While this is an interesting and important phenomenon, my judgment is that it is a second-order effect that does not significantly offset the forces tending to restrain innovation below efficient levels.

Arrow-Debreu world, current consumers should be able to buy and sell oil for delivery on1 January 2050.

Uncertainty is handled in a similar way. For full efficiency not only do we assume markets for future goods, but we also assume markets for contingent goods. Therefore, in principle, we should have a market for oil in 2050 in the event that the average temperature in 2050 is one degree above what is now, another market for oil in 2050 if the temperature is two degrees above what it is now, and so on. Obviously, such markets do not exist, which creates a potential for inefficiency.

Another difficulty is caused by recognizing that human lives are finite. Extending the first theorem to many periods was initially based on infinitely lived agents and the absence of new arrivals. Everyone who would ever be alive is alive at the beginning of the model and remains alive for the duration of the model. Extending the first theorem is much more difficult if we allow new generations to be born and old generations to die. Even defining what we mean by (pareto) efficiency in such a context is not easy[31] and considerable effort has gone into studying the normative properties of overlapping generations models.[32]

Nevertheless, I believe that it has been clearly shown, particularly by von Amsberg (1995),[33] that in a world with overlapping generations and uncertainty we can expect fundamental market failure. The following example illustrates a market failure similar to that identified by von Amsberg (1995), except that the example is recast in an innovation context.

### *8.4. An example of intertemporal market failure*

There are three periods and two generations. Generation 1 (G1) lives in periods 1 and 2 and consumes only in period 2. It receives a storable endowment of 10 in period 1. It can consume the entire endowment in period 2 or it can use part of the endowment to invest in an innovation (such as alternative energy) in period 1. The required investment is 2. G1 obtains no direct benefit from the innovation. Any benefit would be experienced only by Generation 2 (G2). Both G1 and G2 are risk averse.

G2 lives only in periods 2 and 3 and consumes only in period 3. It receives a storable endowment of 10 in period 2. It can consume the entire endowment in period 3. However, if G1 chooses to innovate in period 1, then G2 can purchase that innovation from G1 in period 2 using part of its endowment. In period 2 a negative event might occur (such as the start of significant melting of polar

31 For example, saying that we are looking for a policy that makes everyone better off is not good enough, because it is not clear who 'everyone' is. Does 'everyone' include all potential people? Or does it include only those who actually get born under the policy chosen, in which case the set of people who 'count' is itself policy dependent, leading to logical circularity. Either approach leads to conceptual problems.

32 An early widely cited paper based on an overlapping-generations model is Samuelson (1958).

33 This paper, published in the *European Economic Review*, was based on von Amsberg's PhD thesis done at the University of British Columbia.

ice caps), whose impact occurs in period 3. The probability of the negative event is 0.5. If the negative event occurs, the endowment of G2 is reduced by 4 in period 3. However, the negative event can be prevented or offset by the innovation.

Competitive markets fail to support a feasible pareto-improving transaction in this case. Under competitive markets no innovation occurs. In period 2, G1 will be able to sell the innovation to G2 only if it is needed in the sense that the negative contingency occurs, in which case the innovation will be sold for its marginal value of 4. Otherwise G1 will get nothing for the innovation. In period 1, if G1 chooses to innovate, it faces an uncertain prospect with an expected value of 10. Specifically, it uses 2 units of its 10-unit endowment for the innovation, then has a 50% chance of selling the innovation for 4 and getting consumption of $8 + 4 = 12$. It also faces a 50% probability of not selling the innovation and consuming only 8.

If G1 does not innovate it consumes 10 with certainty. As G1is risk averse, it prefers a sure thing to an uncertain prospect with equal expected value and will not innovate. Therefore, G2 faces the uncertain prospect of consuming either 6 (if the negative contingency occurs) or 10 (if not). Each outcome has 50% probability.

However, there is, a pareto-improving transaction available. If G2 could make a pre-commitment in period 1 to buy the innovation for a price of 2 in period 2, then G1 would be willing to carry out the innovation (as it would consume 10 no matter what) and G2 would have certain consumption of 8, making it strictly better off (as it is risk averse). If G2 committed to paying slightly more than 2 both generations could be strictly better off. Such a transaction is physically feasible and could be mandated by government intervention but will not occur under decentralized competitive markets, as no commitment device is available. Thus, decentralized competitive markets will underprovide innovation in this case.

While the example is very stylized, it is clear that the problem is not an artefact of the specific assumptions. We can add more periods, more generations, more goods, production, discounting, much more general specifications of uncertainty, and other more realistic assumptions without eliminating the basic market failure problem.[34] The fundamental problem is much like the hold-up problem, as it arises from the inability of the second generation to commit itself to paying for the innovation. The missing market is a period 1 market for the innovation in the sense that G2 cannot participate in such a market to sign the needed binding contracts.

34 Indeed the problem would be much worse if we allow for the possibility that G1 cannot be sure of being able to sell the innovation at all, but might just have it appropriated by G2 – but this is really an example of the appropriability problem already discussed, so I abstract from it here.

### *8.5. Other intergenerational issues*

Some readers might object that focusing just on intergenerational market failure misses the primary intergenerational issues. For many the key issue is one of 'stewardship' – the idea that current generations should not impair the planet that is bequeathed to future generations. We are certainly 'using up' the Earth's natural capital at present – oil and other non-renewable resources are being depleted, deforestation and soil erosion are proceeding at significant rates, and we have already discussed issues related to climate change. Either preventing or offsetting such problems will require considerable innovation in relevant areas, such as agriculture and energy. Stewardship is essentially a distributional objective, not an efficiency objective. It is based on some notion of the current generation's obligation to the future – a value judgment that many people hold strongly.

In addition to the purely distributional stewardship objective, it is also possible to invoke a cost-benefit criterion. What I mean by this is that there might be low-cost innovations that, if undertaken now, might have enormous benefits for future generations. Thus, investing in the innovation now would pass a cost-benefit test, but the investment does not take place because the benefit is not experienced by the current generation. For example, an innovation in alternative energy that allowed us to hold off significant melting of ice sheets in polar regions would generate enormous future benefits.

Without getting into the difficult and much studied questions about how future welfare should be discounted, it seems clear that benefit-cost ratios associated with prudential innovation could be substantial. It might not be possible to fully compensate current generations for the costs they incur. However, if the costs are modest and the future benefits are enormous, then failure to take such actions seems a major problem.

### *8.6. Does market failure explain the innovation slowdown*

Do the market failures just discussed provide an explanation of the innovation slowdown? After all, presumably they were present when major innovations occurred in the sectors we have reviewed. Do we really believe that market failure is now holding back innovation in agriculture, energy, transportation, health care, and elsewhere?

I doubt whether market failure is the primary reason for the innovation slowdown. I suspect that innovation is slowing down in most areas because we are approaching physical and biological limits. Larger and larger investments are needed to make incremental gains. It is possible to view essentially all the technological innovation of the past 500 years as 'simply' a matter of harvesting the yield of the scientific revolution. Without comparable intellectual breakthroughs that expand or circumvent what appear to be physical and biological constraints, innovation is starting to get more difficult.

However, from a normative point of view, I suspect that the relevant market failures are increasing in relative importance, taking us further from appropriate allocation of resources to the innovation process. More specifically, it seems likely that the relative importance of both property rights problems and intertemporal market failure have increased over time and that both these problems contribute significantly to insufficient innovation. For example, the potential effects of global climate change and other ecological problems constitute a very large and growing negative externality. Even apart from the intergenerational issues discussed in the previous section, such externalities are important. For example, innovators who succeed in weaning us away from fossil fuels would appropriate only a tiny fraction of the benefits that would accrue even just to current generations.

I would suggest that a reasonable assessment of costs and benefits even for just current generations would imply putting in place major alternative energy systems now, cutting back dramatically on fossil fuels (especially coal and oil), and investing much more in reducing emissions when fossil fuels are used. The failure to do so is a major market failure in both the energy and transportation sectors. If fossil fuel use and fossil fuel emissions were appropriately priced to internalize the negative externalities, this would provide a significantly increased incentive for innovation in alternative energy and for more efficient use of fossil fuels.

I would also suggest that the agricultural sector is subject to dramatic and increasing inefficiency, caused in part by market failure and in part by government actions. For example, the agricultural sector is characterized by inefficient use of water. First of all, water is simply underpriced in much of the world, provided to farmers at much less than its opportunity cost. In addition, there is a strong negative externality associated with water use. A farmer who uses ground water does not take into account the costs to others of the general decline in the water table. If water were appropriately priced, this would provide incentives for development of water-saving crop varieties and for more efficient use of water.

Health care is also subject to significant market failure. For example, infectious disease is driven by an externality problem at the individual level. There is little doubt that individuals suffering from infectious diseases take insufficient efforts, from a social point of view, to avoid transmitting that disease to others. Also, individuals have an incentive to over-use antibiotics, as they do not account for their actions in contributing to antibiotic resistance. This is particularly true of routine 'precautionary' antibiotic use in agriculture. The benefits of medical advances are not easy for innovators to appropriate. In addition, the nature of public intervention in health care creates significant inefficiencies. In Canada, for example, the relentless effort to purge health care of private enterprise probably significantly reduces incentives for innovation.

### *8.7. Policies affecting innovation*

The importance of market failure in the innovation process has been long recognized, although it is less than fully understood. There are many policies that affect innovation. Perhaps the policy most associated with innovation is intellectual property policy,[35] particularly patent policy.

However, the most important policy for stimulating innovation is probably just getting prices right. Prices should properly incorporate the social cost of negative externalities, which would imply, for example, higher energy prices. It is also important to avoid underpricing important resources, such as water. Appropriate prices would, as discussed earlier, promote investment and innovation in alternative energy and in water-saving agricultural technology.

Another area where pricing reform is called for is congestion pricing in transportation. It is now feasible to equip motor vehicles with equipment that meters driving patterns by location and time of day. Driving in congested areas could therefore be priced relatively easily. Prices could incorporate charges for wear and tear on roads and for safety risks to others – using adjustments for the size and weight of the vehicle. A display on the dashboard could indicate when prices are being charged and how much is being charged. Such pricing would induce more efficient use of roads and provide incentives for innovation in transportation, including using lighter and smaller vehicles.

The fourth area emphasized in this paper, health care, could also benefit from improved pricing. While I accept and support the idea that certain basic medical services should be provided essentially free to target populations, I would suggest that much more extensive use of prices in the health system would promote more efficient use of resources and more innovation. Better availability of information (making information about the outcomes of different medical treatments widely available to researchers) would also have a very positive effect.

Innovation is also significantly affected by other policies, including grants and subsidies to university-based research, various aspects of the regulatory and tax systems, and policies affecting innovation finance. I will not take the space to review such policies here but will provide some comments on patent policy.

## 9. Patent policy

Patent policy is targeted at the market failure associated with the inability of innovators to appropriate the benefits of their innovations. By granting an innovator a monopoly right to an innovation for some period of time, patents increase the innovator's ability to appropriate benefits and therefore are expected to increase the incentive to innovate. A secondary benefit of patenting is that it provides for disclosure of information about the patented product, possibly encouraging follow-on research and development. Long regarded as an essential

35 As described on the Canadian Intellectual Policy Office (CIPO) website at www.cipo.ic.gc.ca, there are five areas of intellectual property (IP) policy in Canada – patents, copyright, trademarks, industrial designs, and integrated circuit topographies. The latter two operate much like patents but apply to areas not covered by patents. In these areas IP protection lasts only 10 years rather the 20 years for which patents last.

policy for promoting efficient investments in innovation, patent policy has been subject, in recent years, to significant criticism. Two highly influential critiques are Boldrin and Levine (2008) and Jaffe and Lerner (2004).

Perhaps the most fundamental concern about current patent policy is that it might actually hinder innovation. One very important hindrance is sometimes referred to as the 'tragedy of the anti-commons,' a termed coined by Heller (1998). Just as the traditional 'tragedy of the commons' is based on insufficient property rights, the 'tragedy of the anti-commons' is based on excessive property rights. The basic idea is that proliferation of patents creates so many rights holders over a potential new product that innovation can be delayed or prevented because of the associated transaction costs.[36]

The iPhone, for example, is based on over 200 *new* patent applications[37] and draws on technology covered by hundreds of prior patents owned by a wide range of individuals and organizations. Furthermore, it is far from clear exactly which prior patents are sufficiently relevant to the iPhone to require explicit licensing. The large number of rights holders and significant uncertainty about which patents apply might be expected to encourage litigation or to lead to outright paralysis. Not surprisingly, Apple has been engaged in extensive litigation with companies such as Nokia and Palm over patent rights associated with the iPhone.

A second potential problem is rent-seeking. The patent system might be used by so-called 'patent trolls' to impose, in essence, a tax on innovative firms. These patent trolls typically do little if any innovation and have no serious plan to ever produce anything, but they acquire patent rights of marginal (or sub-marginal) technical relevance to the activities of active firms. Such patent trolls can threaten to use patent-related litigation to disrupt active firms, which often find it easier to pay off such claims rather than incur the expense and disruption of extensive litigation. By threatening such disruptions, these opportunistic patent trolls seek to obtain transfers or 'rents' from genuine innovators.

Both the anti-commons hypothesis and the rent-seeing hypothesis would suggest high levels of litigation. A number of CEOs of major technology companies have stated that they spend more on patent litigation than on R&D.[38] Companies such as Apple, Nokia, Palm, Microsoft, IBM, Intel, and others, maintain very large legal departments dealing with intellectual property. Such costs might be expected to slow the pace of innovation. Companies without such substantial resources to defend against legal predation might be deterred from innovating altogether.

A third potential problem with the patent system is the traditional problem with government bureaucracies. They might not do a good job. Patent examiners

36 There is not a great deal of systematic empirical analysis of the anti-commons effect, but Murray and Stern (2007) find some evidence of such an effect.

37 This statement was made by Apple CEO Steve Jobs during his keynote address at the 2007 Macworld Convention. The transcript can be obtained from www.iphonebuzz.com.

38 This assertion was famously made by Harold Goddijn, CEO of European technology firm, TomTom, and was immortalized on YouTube.

are overworked and not particularly well paid and get little reward for good decisions and limited (if any) sanctions for bad decisions. Jaffe and Lerner (2004) argue that financing changes in the U.S. Patent and Trademark office that increase the reliance on user fees created an incentive for the patent office to err in direction of keeping its clients – patent applicants – happy. The way to keep patent applicants happy is to grant patents.

Most of the criticism of patents has used case studies rather than formal empirical analysis to make the case, and I intend to follow that tradition here. One recent case involved Research In Motion (RIM) Ltd of Canada, the producer of 'BlackBerry' email and cell phone services. In February 2006 RIM paid US$612.5 million to a small Virginia-based firm, NTP. The patents held by NTP were of questionable merit and some key patents were tentatively ruled invalid by the U.S. patent office after a review requested by RIM. However, NTP used sympathetic local courts in Virginia to threaten RIM with significant disruption and obtained a large settlement that many observers view as wholly unjustified.

NTP is a classic patent troll, consisting largely of lawyers and legal support staff. It does essentially no research and produces little if any tangible output. It simply acquires patents and seeks to earn returns from them, either by licensing them or by bringing lawsuits against successful innovators. This case illustrates the rent-seeking aspect of the patent system, as it highlights the significant shift in resources away from production of wealth (i.e., research and development) to fighting over the distribution of existing wealth (i.e., to transfer-seeking through the legal system).

A second case is the Amazon.com 'one-click shopping' patent, granted in 1999. Amazon.com is a pioneer in online sales of books and other products. The patent describes the idea of allowing a customer to click a single icon that brings together the credit card number, the address of the customer, and product information, essentially reducing the primary purchase transaction to a single click. About three weeks after receiving the patent, Amazon brought a suit against Barnes and Noble, another online bookseller offering a one-click sales option to customers.

The Amazon suit created considerable controversy, including boycotts against Amazon. In light of the large amount of negative publicity, Amazon reached a settlement with Barnes and Noble that was believed to impose little cost on Barnes and Noble. Amazon has not brought any additional suits against internet vendors, despite the widespread use of 'one click shopping.'

Many observers, including Amazon programmers, expressed surprise that something as obvious as one-click shopping could be granted a patent. Other users of one-click shopping methods who, it turns out, predated Amazon.com, did not apply for a patent because the concept seemed so obvious. After all, many things on the Internet are done with a single click and, presumably, making any internet transaction as simple as possible is an obvious objective. In an April 2007 decision (*KSR International v. Teleflex*) the Supreme Court of the United States found that the standard being used by lower courts for deciding on whether an innovation was 'obvious' was too generous to patent applicants.

The third example is perhaps the most extreme. Jaffe and Lerner (2004) describe the case of a patent for the sealed crustless peanut butter and jelly sandwich obtained by J.M. Smucker Co. in 1999. The 'innovation' involves making a peanut butter and jelly sandwich, removing the crusts, and pressing the edges together. Smucker sent a cease and desist order in 2001 to Albies's Foods, a small grocery and caterer in Gaylord, Michigan, that had a long tradition of selling such sandwiches. Instead of giving up (the economically rational thing to do) Albie's fought the case in court, pointing out that the so-called crustless sandwich was essentially a 'Cornish pastie' of the type that had been popular in Michigan since the nineteenth century and in Cornwall, England, long before that. The case was settled privately and Albies still sells pasties.

To an outsider, this case seems absurd at several levels. First, it seems that the patent office simply erred in granting a patent for something that was not original. Second, this does not seem like an appropriate class of activity for patents. Do we really believe that this kind of 'innovation' – slight variations on peanut butter and jelly sandwiches – needs to be protected by patents? Third, litigation over the patent has been very costly for all parties, the primary beneficiaries being lawyers. Admittedly, any large organization (such as the U.S. patent office) is likely to produce the occasional error. However, Jaffe and Lerner (2004) argue that this case, while extreme, is representative of a pervasive set of problems.

While some observers, like Boldrin and Levine (2008), advocate an extreme approach involving effective abolition of the patent system I favour a number of specific reforms. First, all areas should not be treated equally. Economic principle would suggest that stronger patent protection should be provided where the underlying market failure is most severe. In particular, the case for significant patent protection of pharmaceuticals seems strong. New drugs are very expensive to develop but, once developed, are very easy to copy and very cheap to produce. I have argued earlier that the pharmaceutical industry has been the source of dramatic improvement in well-being, and it is hard to see how the industry could operate without significant patent protection. In addition, individual drugs are not very susceptible to the anti-commons problem.

On the other hand, it is hard to see how products like variants on the peanut butter and jelly sandwich warrant protection. More important, it would be useful to see a clearer line between 'ideas' and 'discoveries,' which are not patentable, and 'inventions,' which are. Those of us in the academic world understand how important the free flow of ideas is for intellectual progress. Many academics and others have expressed concern that genetic code and entire biological entities can be patented. The principle impact of such patents is to prevent others from doing research, and it is hard to believe that such patents do anything to encourage innovation. I would also favour eliminating business process patents, reducing the length of patents in most areas, and generally requiring a larger inventive step before granting a patent. Stricter licensing requirements and 'use it or lose it' provisions would be valuable, as would legal reforms to limit rent-seeking through nuisance or predatory IP lawsuits.

I would not expect patent reform to have a major impact on innovation in the industries emphasized in this article. However, it is important to restore the free flow of ideas and basic research related to genetic manipulation, as such areas are likely to be fundamentally important in both agriculture and health care over the next century. I am concerned that the patent process as currently constituted is likely to have an anti-innovation effect in these areas.

If we consider the major innovations, including many cited in this paper, the profit motive has seemed a rather minor consideration. The great medical innovators, such as Jenner (vaccines), Lister (sterilization), Rontgens (x-rays), Fleming (antibiotics), and others, appear to have been completely indifferent to financial incentives. They did care about professional stature and were strongly motivated by intellectual curiosity. For such people, having a free flow of ideas is very important. In today's biotechnology world such scientists would likely be held back by gene patents and related forms of intellectual property.

## 10. Concluding remarks

The discussion of innovation in this paper might be viewed as cautionary, if not downright pessimistic. In particular, I argue that the pace of innovation in important areas such as agriculture, energy, transportation, and health care has slowed significantly in recent decades. I would also suggest that other important industries have a similarly modest recent record of innovation. The paper also expresses concern that current and projected rates of innovation might not be sufficient to improve or even maintain living standards in the face of still rapidly growing population, global warming, and other challenges of the twenty-first century.

Trying to predict innovation is a challenging and perhaps foolhardy task. Predictions made in earlier decades often seem quaint or amusing today. In the past, grim predictions about agriculture and energy, among other areas, have sometimes preceded dramatic innovations. We are living through a burst of innovation in information and communications technology at present that may yet generate even more fundamental and far-reaching benefits than it has done already. Furthermore, perhaps we are on the verge of a surge of innovation related to genetic engineering that will greatly improve healthy life expectancy and reduce concerns related to food scarcity. At a minimum, I acknowledge that my concerns about innovation are highly speculative.

Some economists have argued that the irregular pattern of innovation in a given industry can be explained as similar to the 'punctuated equilibrium' theory of evolutionary biology. Roughly speaking, punctuated equilibrium theory-suggests that evolutionary changes in a species or related group of species are concentrated in short periods, with relative stability in the genome most of the time.[39] Applying this idea to innovation implies that within a specific area, such as transportation or agriculture, we should expect brief periods of rapid technological change surrounded by relative stability. According to this view, we should not be alarmed if the pace of innovation in a particular area declined after a burst of innovation, as seems to have happened, for example, in agriculture after the green revolution.

Even so, I suggest that it would be useful to encourage innovation in important areas by properly aligning prices of such things as energy and water with their full social cost and by undertaking significant reform of the patent system and other policies affecting innovation.

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39 The theory of punctuated equilibrium in evolutionary biology is attributed to Eldredge and Gould (1972). While there is no doubt that the pace of evolution is highly variable, often arising from exogenous climate change, it is far from clear that there is an endogenous biological process that generates a systematic variation in the speed of evolutionary change.

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