THE ECONOMICS OF SCIENCE AND THE FUTURE OF UNIVERSITIES

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by

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[+] This talk draws heavily on my joint work on endogenous growth theory with Philippe Aghion, and also on many ideas that I learned from fellow members of the Economic Growth and Policy Program of the Canadian Institute for Advanced Research during my association with that program from 1994 to 2003, especially Dick Lipsey, Paul Romer and Nathan Rosenberg, none of whom bears any responsibility for the contents. I would also like to thank the members of the Department of Economics at the University of Saskatchewan for their hospitality at the time of the lecture and for their extreme patience in waiting for the written version.

Introduction

It is an honour to be giving the 16th lecture in this series honouring the memory of Mabel Timlin, one of the pioneers of modern Canadian economics. My talk will concern an area of economics to which I don't think Timlin ever contributed directly, namely the theory of economic growth, but my main message concerns something to which she contributed a lot in many ways, namely the future of universities. I will examine the interactions that take place between science and the economy, and the role that universities play in that interaction, from the point of view of the new growth theory that has been developed over the past decade and a half. I will argue that strong economic growth depends on strong universities that promote the academic goals of open science but are also actively engaged with private industry in developing new technologies. Such involvement with commercial and industrial interests creates a tension within universities, between economic and scientific values, a tension that is being heightened by the emerging biotechnological revolution. The future of universities will depend on their ability to manage that tension wisely and to harness its creative potential. The challenge will be to preserve and protect scientific values while at the same time becoming increasingly involved with interests opposed to those values. In my view the future of economic growth will also depend on how universities respond to this challenge.

1. Technological innovation as the mainspring of economic growth

I have spend much of my time over the past 15 years or so looking into the question of economic growth - why have some countries grown so much richer than others, and why are industrialized countries like Canada so much richer now than they were in the past. Like almost everyone else who has examined the question I am convinced that the key to economic growth in the long run is innovation. Innovation is what creates the technological progress that continually offsets the drag of diminishing returns that pessimists from Malthus[1] to the Club of Rome[2] have predicted will bring economic growth to an end.

According to the law of diminishing returns, a rising population working on a planet with a fixed amount of land will produce an ever decreasing amount of food per person. If the population continues to grow exponentially, the output of food per person must eventually fall below the level needed to sustain life. At that point Malthus's "natural check" of starvation will reduce the population to a sustainable level, a level at which the average person has just enough land to work with to stay alive and to reproduce with zero population growth.

[1] Malthus (1798).

[2] Meadows et al. (1972).

An implication of this logic is that in the long run not only is population growth impossible but so is growth in output per person, which will always tend to revert to the subsistence level. In the short run people might raise their standard of living by investing in more capital – acquiring more farm implements or clearing more land for example – but eventually the finiteness of the planet will impose diminishing returns on these efforts too, and per-capita income will stabilize. If population growth is controlled then the standard of living need not fall back to the subsistence level but it will nevertheless cease to grow.

There is nothing erroneous about the law of diminishing returns, provided that technological knowledge remains unchanged. Fortunately it has not remained unchanged. Real living standards, as measured by per-capita GDP, have continued to grow from the late 18th Century until today, at a rate which if anything has been increasing rather than decreasing. The world now has 6 times as many people as when Malthus wrote, and about 9 times as much GDP per person.[3] Instead of suffering from rising starvation we continue to produce more and more food per person. For example, Easterly (2001, p.88) points out that since 1960, while the world's population has doubled, the world's food supply has approximately tripled. The reason is that we now know how to coax much more food out of any given amount of land than before, and the reason for this is a succession of innovations – better seeds, better pesticides, better fertilizers, better farming techniques, and better farm implements.

Thanks to technological innovations in agriculture, countries like Canada in which over ninety percent of the population once worked in agriculture can now feed themselves, and even export a large share of their food production, while employing only 2 or 3 percent of the population in agriculture. As a result, the output of advanced countries now consists almost entirely of manufactured goods and services. But even in modern non-agrarian economies, technological innovation is still needed in order to offset diminishing returns and thereby to sustain growth in living standards, and it has indeed taken place. The average Canadian is about three times as rich today as fifty years ago, not because we produce more typewriters, vacuum-tube radios and rotary-dial telephones, using the same processes as fifty years ago, but because we are now able to produce new products, like jet airliners, high-definition television, computers and cellular phones, that were not possible before, and we use new production processes, like lean manufacturing techniques and just-in-time inventory management that produce and deliver goods more efficiently than before, and medical advances like laser surgery, organ transplants and angioplasty that enable us to live longer and healthier lives.

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[3] Maddison (2001, p. 28).

2. Science, technology and economics

Once we accept that economic growth is driven by technological progress, it is a short step to recognizing the fundamental importance of science as a factor in economic growth. Clearly we would not now be enjoying the benefits of television, the computer, jet transport, laser surgery or modern pharmaceuticals if no one understood the fundamentals of electricity, solid-state physics, chemistry or aerodynamics. Because technological progress depends to a large extent on advances in basic science therefore economic growth is also highly dependent on science.

It would be a mistake however to see the causal connection between science and the economy as going in one direction only. For there are important feedbacks from the world of commerce to the world of science. Economic factors play an important role, sometimes a decisive one, in determining the pace and direction of scientific progress. Although a model of unidirectional causation, in which scientific progress leads to technological progress, which in turn leads to economic growth, with no feedback from the economy to science or technology, is often taken as a starting place for teaching the theory of economic growth, this "neoclassical" model[4] portrays a misleading picture of the causal effects at work and of the crucial role that universities play on the interface between science and the economy.

The idea that science is affected by commerce looks at first glance crass and implausible. Scientists, at least the best ones, are driven by curiosity, not pecuniary interest. What they do is an intellectual activity, not economic, and success is measured by explanatory power, not profit. But although this is certainly true there are nonetheless several important channels through which economic considerations affect the course of science.[5] To begin with, science is an expensive activity that uses a lot of capital, labour and raw materials. And as it progresses it seems to get more expensive. These resources all have alternative economic uses, and the pace of science will be retarded if society becomes less willing to forego these alternatives, a point which is implicit in the argument of those scientists who plead for funds to construct particle accelerators, satellite telescopes and the like. A speedup of economic growth typically relieves fiscal pressures on governments and makes them willing to devote more resources to science, thus helping to accelerate the pace of scientific progress.

Another channel through which economic factors affect the course of science is the market for scientists. As in all other professions there is a limited supply of willing workers, the number of which depends, other things equal, on the level of wages being offered. Even the most unworldly of scientists must eat, and will therefore not work if not paid. Beyond this everyone

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[4] Solow (1956) and Swan (1956).

[5] The following draws on the excellent survey by Stephan (1996).

has alternative uses for his or her time, and the greater the wage that can be earned in other occupations the fewer will choose to enter science. Thus the fact that economic growth is associated in the long run with an economy-wide rise in real wage rates means that it directly impinges on the conduct of science by affecting the quantity, and also the quality, of human talent engaged in science.

Yet another channel through which commercial factors play a role in scientific progress is industrial research, conducted by scientists in the R&D laboratories of private business enterprises. To a large extent private firms concentrate on applied research and development (R&D), but they also carry out a significant amount of basic scientific research. According to the National Science Foundation over 22% of all the basic research conducted in the United States from 1993 through 1997, measured by the dollar value of expenditures, was performed by private enterprises.[6] Nobel Prizes have been won by scientists in the R&D laboratories of AT&T, IBM, Smith Kline and French (now GlaxoSmithKline), Sony and General Electric.

Although science may be a non-economic activity for the scientists hired by industrial research laboratories, it is certainly an economic activity from the point of view of the firms that own and operate the laboratories. How they benefit from contributing to fundamental scientific knowledge is an interesting question. To some extent it is because science is not a spectator sport. In order for a firm engaged in R&D to benefit from current developments on the frontiers of science it helps to have people actively working on those frontiers. Even to recognize what scientific developments are worth paying attention to often requires someone who is engaged in pure research.

Moreover, many firms have found that the best way to attract scientists to work for them is to offer them the opportunity to pursue their research interests, whatever that might lead to, in exchange for being on hand to help out with the basic mission of the firm when called upon. In that sense the situation of a scientist working for an industrial laboratory is like that of one working for a university, who is free to work on whatever scientific research seems most attractive at the time, in exchange for being willing to help out with the university's primary teaching mission. The important thing to note here is that whatever the motivation, the extent to which private enterprises engage in pure scientific research will respond to incentives. Increased competitive pressure and deregulation, for example, appear to have been key factors in the recent scaling back of purely scientific research by major industrial laboratories in the United States.[7]

The increasing focus by private research laboratories on more applied R&D does not

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[6] National Science Foundation (2002).

[7] See for example Odlyzko (1995).

imply however that scientific progress is ceasing to be affected by the incentives to engage in R&D. This is because, as Nathan Rosenberg (1982) has argued at length, the connection between science and technology involves important feedbacks from technology to science. Privately conducted R&D, aimed at solving mundane practical problems arising in profit-seeking business enterprises, apparently far from the realm of pure science, have often been the source of fundamental scientific breakthroughs. For example, Pasteur was searching for a remedy to problems of putrefaction in wine-making when he made the discoveries that created the science of bacteriology. Torricelli was working on the practical problem of devising a more efficient pump when he demonstrated that the atmosphere has weight. Joule was searching for power sources for his father's brewery when he discovered the principle of the conservation of energy. More recently, Penzias and Wilson were exploring the possibility of satellite communication for the AT&T corporation when they discovered the background radiation that confirmed the detailed predictions of the big bang theory of the origin of the universe; not only were Penzias and Wilson not intending to confirm the big bang theory, they were not even aware when they made their discovery that it was predicted by the theory.

As Rosenberg has argued, these and many other examples illustrate that it is wrong to think of technology as "applied science," as in the linear neoclassical growth model. Instead, the right way to think about technology and science is that technology is a body of knowledge about *what* works, whereas science is a set of principles explaining *why* certain things work. Very often the technology precedes the science, rather than the other way around. For example, the science of aerodynamics was not sufficiently advanced to explain why birds can fly until the Wright brothers found out how to make humans fly. As another example, Vane discovered the principles underlying aspirin's anti-thrombotic effect only after practicing physicians had already discovered that such an effect exists and some had even begun prescribing aspirin for the prevention of heart attacks and strokes.[8] Indeed, technological breakthroughs sometimes set the agenda for fundamental scientific research, as was the case for solid-state physics after the research programme launched by Bell Laboratories to find an alternative to unreliable vacuum tubes led to the invention of the transistor in 1947 by Bardeen, Brattain and Shockley.

The upshot of this mutual interdependence between science and technology is that even if all private R&D by business enterprises consisted of purely profit-oriented applied research, the economic considerations that govern the pace and direction of industrial R&D would still have a major effect on the pace and direction of scientific progress.

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[8] Rosenberg and Gelijns (1996).

3. Intellectual capital and market failure

Research is an economic activity similar to the more conventional economic activity of investment in plant and equipment. In either case the activity requires the expenditure of current resources and produces an asset yielding future benefits. The main difference is that in the case of research the asset takes an intangible form, consisting of scientific and technological knowledge; research produces intellectual capital rather than material capital. This difference is important, and it implies that a nation's R&D, and especially its basic scientific research, should not be governed by the same unbridled market forces that work well in other domains of the economy. But it does not imply that economics must be abandoned when we think of how to organize scientific research. On the contrary, economics has a lot to say about the production and use of intellectual capital. Indeed the analysis of knowledge accumulation is at the heart of the new growth theory that has displaced the neoclassical theory of Solow and Swan from the frontiers of macroeconomics.[9]

From the view point of economic theory the main difference between intellectual capital and material capital is that the former is a "non-rival" good.[10] Once an idea is produced it can be used any number of times by any number of people at no extra cost, whereas in order for twice as many people to drive a car, for example, twice as many cars must be produced. Thus knowledge is like a house with room for any given number of people. Or as Thomas Jefferson once wrote, it is like the light of a candle, which is not dimmed by using it to light another person's candle.

Free markets are not capable of organizing the production and use of non-rival intellectual capital as efficiently as they do rival material capital. The reason is that privatizing an idea creates an impediment to the free use of that idea. From society's point of view it costs nothing for someone to use the idea of a "do loop", for example, when writing a Fortran program. But if every programmer had to pay a royalty to the inventor of the concept every time he or she used it, less efficient work-around routines would be used, the cost of programming would be raised artificially, and as a result society would end up with fewer and less efficient computer programs. Of course there is nothing wrong with having a lesser quantity or quality of something if as a result we can have more of something else. But in this case, because the do loop is a non-rival good, economizing on its use does not free up any resources with which to produce something else. The impediment to using it thus creates a dead-weight loss to society.

This particular market failure has important consequences for scientific progress, because

[9] See Aghion and Howitt (1998) for an account of the new theory.
[10] Romer (1990).

scientific knowledge grows through contributions that build on past contributions, in cumulative fashion. Even the non-Popperian theories of Kuhn (1962) and Lakatos (1970), in which scientific progress involves paradigm shifts and competing research programmes, admit that much of what is learned in one paradigm or research programme survives when there is a revolutionary change in the discipline. Also the accumulation of anomalous findings by various researchers is what Kuhn believed typically leads to a paradigm shift. Artificial impediments to the public dissemination of knowledge are thus impediments to scientific progress, because they make it more difficult for people to build on the ideas of others, and therefore they also impede technological progress and long-term economic growth.

Any efficient organizational arrangement for the production and use of intellectual capital thus needs to deal with more than the usual problems of giving people the incentive to produce enough and of controlling the quality of what is produced. It must also cope with the problem of giving producers an incentive to share the idea widely, or better still freely. A free market provides incentives for production through the profit motive. When the demand for cars goes up, manufacturers respond by producing more because this raises their profits. Likewise a free market provides incentives for quality control, because manufacturers soon learn that shoddy goods command low prices. But the free market provides no incentive to share. In an unregulated free market arrangement, a firm might still conduct R&D, but only to the extent that it could keep the resulting ideas secret from its rivals. The accumulation and dissemination of knowledge would be artificially constricted, and the result would be slower technological progress and slower economic growth.

4. Two institutional arrangements

Fortunately the world does not operate through markets alone. In situations where free markets do not function efficiently, other organizational structures frequently emerge. Such is the case for the production and use of knowledge. Indeed in almost all advanced countries there now exist two parallel sets of institutional arrangements: the patent system, in which market forces are constrained by legal restrictions on the use of intellectual property, and open science, which is based on a sophisticated self-reinforcing code of conduct. Both systems provide a partial solution to the threefold problem of producing knowledge, controlling its quality and sharing it.

Under the patent system the incentive to produce knowledge is provided by the prospect of monopoly profits. The inventor of a new product or process can get a patent, or in some cases a copyright, that prohibits any competitor from producing that particular product or process without the inventor's permission. This selective elimination of competition allows the inventor to earn a profit in situations where unrestricted competition would have reduced profits to zero.

It thus provides a reward to a successful inventor. Quality control under the patent system is provided by the usual market test. Even a monopoly position will fail to generate enough profits to cover the cost of inventing a low-quality good that consumers shun.

The incentive to share ideas under the patent system is provided by the disclosure requirement of patent laws. Although the details vary from country to country, all patent laws involve some requirement to the effect that a successful applicant must provide a clear description of the product or process to be covered by the patent. If the application succeeds, this description is available to anyone who examines the patent documents, who in many cases can then learn all that is needed to replicate the invention.

The patent system thus deals with the conflict between the incentive to produce ideas and the incentive to share them by making a distinction between the object being patented and the idea behind that object. While it prohibits anyone from using the object without compensating the patent holder it does not restrict anyone from using the idea. Indeed it forces the patent holder to disseminate the idea. Someone deciding on whether or not to patent an idea thus has to make a tradeoff between the monopoly profits that come from preventing production by rivals and the possible losses that might result from a rival's use of the idea. That is, someone that sees a detailed description of how I produce my patented golf club might easily see a possible improvement that I have overlooked, and start producing and marketing an even better club that steals my market. In many cases the inventor may decide that the price of disclosing one's secrets is not worth paying, especially if what is being produced is not easily reverse-engineered.[11]

Open science provides a different incentive to produce knowledge. It comes from the recognition one gets from having been the first discoverer or creator of that knowledge. Recognition takes the form of citation by other scientists, the respect of one's peers, honorific titles, prizes, medals, invitations to deliver prestigious lectures, opportunities to influence the direction of research within one's discipline by taking a leading part in the peer review process and even opportunities to influence one's broader community by taking part in commissions, writing books and pamphlets, and engaging in other such activities to which entry is facilitated by a strong reputation for success in research. The greatest form of recognition comes when one's name is immortalized by being attached to an idea, like Boyle's Law, Planck's constant or the Cobb-Douglas production function.

Although the satisfaction of being honoured by one's peers in these ways is for many scientists the principle reward to successful knowledge creation, it is not the only reward. Curiosity and the private satisfaction that will come from having cracked some tough problem are enough to keep many of the best scientists working hard at their research. But even those who see themselves as mainly driven by curiosity are rarely unmoved by seeing recognition go to someone else for what they think is their own discovery. As any reader of Watson (1968) knows, competition to be recognized as the first can be as intense as any commercial competition. Moreover, the same recognition that brings honour also brings pecuniary benefits. Citations, prizes and a good reputation can be and usually are converted into higher salaries and more grants, honoraria, contract work and consulting fees.

The incentive to share information in open science comes from the imperative to publish or perish. All credit for a discovery goes not necessarily to the first who makes it but to the first who publishes it. As in the patent system there is winner-take-all. The second person to publish an idea gets no more credit than the second person to the patent office, except from citations made in error or by one's friends, students and members of the same citation ring.

Quality control is provided under open science not by the market test but by peer review and an elaborate self-enforcing ethos, which the sociologist of science Robert K. Merton analyzed in a series of fascinating studies[12] and which John Ziman (1994) refers to by the acronym CUDOS:

- C Communalism – The scientist identifies not so much with his or her employer as with the community of scientists. Science is a collective enterprise and everyone is expected to share with others.
- U Universalism – The scientific community is open to everyone. Exclusion for any reason other than violation of CUDOS is unacceptable.
- D Disinterestedness – As a scientist you are expected to treat your own creations with as much objectivity as if they were someone else's, even when your every neuron is craving praise.
- O Originality – No credit is given for copies, only for the first.
- S Scepticism – All contributions, no matter how eminent the contributor, are subject to critical analysis and testing.

The culture of open science built on CUDOS is maintained to some extent by the threat of ostracism. Plagiarism, fraud and misrepresentation are punished by severe loss of reputation,

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[11] Moser (2003) provides historical evidence to the effect that because of these considerations the absence of a national patent law in some countries in the 19^{th} Century shifted inventions in these countries towards industries in which there was a relatively high cost of reverse engineering.

[12] Merton (1973)

that is by severe loss of the primary reward that scientists give each other. As Ziman points out, open science is a kind of market, in which contributions to knowledge are exchanged for recognition, but it is unlike a commercial market in the sense that recognition is not transferable to someone else in a secondary exchange the way money is.

Generally speaking, the incentive to produce knowledge is stronger under the patent system, which allows great fortunes to be made. The incentive to share is definitely stronger under open science, which gives no credit to those who do not reveal their discoveries to the world. Disclosure requirements under the patent system are often not enough to make the idea useable by others, since crucial details can often be left out. This is especially true when what is being patented is itself an intangible idea, like a process or an algorithm. For in these cases it is not clear how to make the distinction between the object being patented and the idea behind that object. Thus anyone wanting to use the idea without the patent-holder's permission runs the risk of being sued for violating the patent.

Indeed the chilling effects of patent litigation can be so great that the patenting of a discovery will lead to even less sharing of the idea behind it than if there had been no patent and no disclosure. For if an idea is patented it might never be used by others for fear of litigation, whereas if it had not been patented it might have become widely used after having entered the public domain through reverse-engineering, through someone else discovering it independently or simply through the grapevine.

The patent system thus tends to work better for very applied knowledge, where (a) the object being patented is concrete and specific, a particular type of medicine for example, and can therefore be distinguished easily from the idea behind that object, (b) the potential spillovers that can be realized from sharing the idea are less, (c) the immediate commercial opportunities opened up by the knowledge are greater than in the case of more basic knowledge and (d) the market test of quality is appropriate. Relatively little fundamental scientific research is conducted under the patent system, largely because most fundamental discoveries do not lead immediately, or even at all, to a commercially viable product or process. Likewise, relatively little applied research is conducted under open science, where the imperative to publish or perish is destructive of monopoly rents, and where in any event relatively few applied innovations would merit recognition by the scientific community.

5. The role of universities

One of the most important roles that universities play in the process of economic growth is to facilitate the cumulative growth of scientific knowledge by acting as repositories and disseminators of knowledge. Indeed, Bekar, Carlaw and Lipsey (2003) argue that the early development of autonomous universities that foster the sharing and perpetuation of knowledge is a main reason why the Scientific Revolution, and ultimately the Industrial Revolution, took place in the West rather than in China or the Islamic world. As I have already argued, this is a role that cannot be performed by private firms, who have little or no motivation to disseminate knowledge.

Universities also play a crucial role in the growth process by supporting the culture of open science, which could not persist without strong universities. Scientists need resources and a great deal of autonomy to take part in a life governed by CUDOS, and few institutions other than universities are willing to given them those requisites. For although open science is a collective enterprise, CUDOS is a highly individualistic ethos, in the sense that it attaches the highest value to individual creativity. The greatest recognition goes to those who successfully pursue an agenda that no one else had recognized as having merit. But the kind of eccentricity that leads one down such a path is rarely tolerated in private corporations, whose culture in this respect is a collective one that rewards employees for subordinating their private goals to the mission of the organization and discourages them from following a different drummer.

A less obvious, but in my mind just as important, role of universities in the growth process is to facilitate the two-way exchange of knowledge between science and technology. Universities are engaged to a much greater degree than is commonly believed in research of a very applied nature. For example, during each year from 1990 through 2001, between 25% and 35% of all research conducted within universities in the United States was classified by the National Science Foundation as applied research or development.[13] Indeed much of this applied research actually consists of product innovation – the development of such products as computers, laboratory equipment, diagnostic machinery like the MRI, and other patentable devices.

By the same token, universities do not just participate in open science, they are also heavily involved in the patent system, increasingly so in the United States since the Bayh-Dole Act of 1980 which allowed universities to hold patents on innovations resulting from government-sponsored research conducted under their auspices. Patents have become a significant source of revenue for many universities. In 2002, the last year for which I could find data, the total licensing income for all universities in Canada and the United States exceeded $1.2 billion (US).[14] Stanford University has earned a total of over $150 million from one spectacularly successful patent alone, the Boyer-Cohen patent for recombinant DNA.

[13] National Science Foundation (2001).
[14] Association of University Technology Managers (2002).

Both the involvement of private industry in open science and the involvement of universities in the patent system reflect the basic complementarity between science and technology that Rosenberg has stressed and which I referred to earlier in this talk. That is, just as private business firms find it helpful to participate in fundamental scientific research in order to facilitate their technological development, so universities have learned that their fundamental research efforts are enhanced by having close contacts with current technological developments. This could hardly be otherwise. How could science - the study of why things work - progress without knowing technology – what things work?

Because of their complementarity, both science and technology progress more rapidly when they can feed off each other. This is why industry and academia both have a lot to gain from each other. Industry needs to keep abreast of what is happening on the scientific frontier, most of which is taking place within universities. Moreover, even when they are hiring scientists to do their own R&D aimed at patentable innovations, private firms often find it useful to encourage these scientists to participate in open science as a way of determining who is keeping up and who is not, converting the recognition that comes from widely cited publications into promotion and monetary gain much the same way that universities do.[15]

Likewise, academia needs to keep abreast of the problems and challenges facing private industry and to keep informed about new technologies that are continually arising and posing new scientific questions. Academic research that maintains an ivory-tower distance from the broader community tends to become sterile. This is true especially in engineering disciplines but to some extent it holds true in almost all fields. Thus Rosenberg and Nelson (1994) have argued, for example, that a great strength of the American university system, as compared with most European systems, is its openness to connections with industry, commerce, agriculture and government, and its willingness to let challenges and opportunities arising in these other sectors of society shape not only the research that takes place within their realm but also the programmes they offer to students.

To illustrate, American universities formed separate departments of computer science well before any European university chose to do so. Getting an early lead was no doubt critical in putting American universities on the path to becoming leaders in the field. Canada's own University of Waterloo was among those early leaders that continue to excel. As another example,[16] chemical engineering had its origin as an academic discipline at MIT in the United States when Arthur D. Little unified the study of what had been a welter of different

[15] Cockburn, Henderson and Stern (1999).

manufacturing processes, in such diverse industries as petroleum-refining, rubber, leather, coal, food-processing, ceramics and glass, sugar-refining, explosives, paper and cement, by showing that all such processes could be decomposed into a small number of "unit operations," which were common across all applications. Little's creative insight undoubtedly owed much to his extensive consulting activities in a variety of different industries, the kind of activities that would have been looked upon with much less respect by academicians in Europe at the time than in the United States.

In my view, recognizing the reciprocal dependency between science and technology and the resulting reciprocal dependency between universities and the broader community is critical for understanding the role of universities in the process of economic growth. Technological innovation, the mainspring of long-term growth, cannot be sustained without fundamental scientific progress, and scientific progress in turn cannot take place without universities to train scientists, to preserve the culture of open science, and also to facilitate the potential spillovers between science and technology that keep science progressing. Universities cannot perform these tasks effectively without becoming engaged actively in frontier technological developments taking place around them.

How economic growth can be helped by universities willing to get involved in technological developments is illustrated by the critical role that land-grant colleges played in creating and disseminating the technological advances underlying much of the remarkable productivity growth in US agriculture, starting with the passage of the Morrill Act in 1862, which was intended to support agriculture and the mechanical arts.[17] The agricultural experiment stations that these colleges operated were instrumental in one of the most successful R&D programmes in US economic history, aimed at the development and diffusion of hybrid corn, a programme which universities undertook in conjunction with private seed companies and which resulted in dramatic increases in per-acre yields. Griliches (1958) has estimated that the social rate of return to these R&D expenditures was at least 700% per year.

A more recent example comes from information technology, the source of much of the productivity growth in the US economy for the past decade or more, many of whose basic innovations originated in close cooperation between US universities, private industry and the US government, especially the Department of Defense. The first fully operational electronic digital computer for example, ENIAC, was built at the University of Pennsylvania under an Army contract. Silicon Valley, the source of many of the basic building blocks of the computer age, is

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[16] See Rosenberg (1998) for a concise account of the emergence of chemical engineering as an academic discipline.

a product of Stanford University's decision to create an industrial park for high-tech companies whose activities might be beneficial to Stanford. The protocols of what later became the internet were developed as part of a US Department of Defense project to create a network linking computers in different universities, all of which were actively participating in the project.

6. The biotechnology revolution

The complementarities between science and technology are nowhere greater than in the life sciences, where, as Rosenberg and Gelijns (1996) argue, post-innovation experience has proven to be especially critical for progress. It is always true that one innovation is not enough. Version 1.0 always leaves room for improvement and needs to be debugged. Quite often the need for debugging and the nature of improvements needed become apparent only long after the innovation has been implemented, as a result of repeated experience. This is true in medicine perhaps even more than in software development, because the human body's response to interventions is unpredictable. That is why in the life sciences it is especially useful to have basic and applied research being done in the same institutional setting. It is undoubtedly why the teaching and practice of medicine have evolved so closely together, through the institution of the teaching hospital. It is probably also why university involvement in the patent system is greatest in the life sciences. For example, Rosenberg and Nelson (1994) found that in 1990 in the United States, out of 7 categories of patents in which universities held at least ten percent of existing patents, 6 of them were in the life sciences, categories such as genetic engineering and surgery.

The strong synergies between life sciences and biotechnology are also evident in the massive private investments that have taken place under industry-university partnerships, and in the increasing involvement of private industry in even basic university research. The former president of Stanford University, Donald Kennedy (1996), has written that in the 1970s he began to notice that private firms were increasingly interested in becoming involved at a basic stage in scientific projects, especially in the area of life sciences. This involvement of commerce and industry in basic life science has accelerated with the biotechnology revolution that we are now living through.

Perhaps the most celebrated recent example of commercial involvement in basic life science has been the participation of Celera Genomics, the company led by the scientist J. Craig Venter, in the human genome project. Although the scientists involved in the initial project that later merged with this private initiative felt that Celera's approach was too crude to be scientifically valuable, and although some biologists doubt the fundamental importance of the

[17] Huffman and Evenson (1993) document this role at length.

project, nevertheless it was a project that could not have been undertaken without a huge amount of fundamental scientific expertise. It took the sort of scientists that would normally be pursuing a career governed by CUDOS in a university, not seeking a fortune in business.

Another sign of the increasing involvement of private firms with academic science in the biological area is the number of private spin-offs and industrial parks that surround many of the major universities in North America. Kendall Square near MIT is increasingly becoming a centre of activity not just of software developers with ties to MIT but of firms such as BioGen with ties to biological research at MIT. We see a similar development with Innovation Place here in Saskatoon, with close ties to the life sciences at the University of Saskatchewan.

The increasing involvement of commercial interests in the life sciences is part of a long-term trend, in which technology is becoming increasingly dependent on science in a direct and unmistakable manner. It is often pointed out that the key innovations of the Industrial Revolution were created not by scientists but by "tinkerers" with little or no scientific training. This doesn't mean that science was an unimportant factor in fostering the Industrial Revolution. Indeed, as mentioned above, Bekar, Carlaw and Lipsey (2003) have argued that the existence of autonomous universities allowing scientific knowledge to cumulate was a crucial reason why the Industrial Revolution took place in Europe rather than elsewhere. Moreover, Jacob (1997) has argued that it was the presence of a strong scientific component in British culture in the 18th Century, supported by such institutions as the Royal Society, that accounts for the Industrial Revolution having taken place in Britain rather than elsewhere in Europe. But it is at least possible to imagine the major technological innovations of the 18th Century having been made by people with no understanding of the current state of science. This has become less and less imaginable with subsequent major innovations. The key inventions of the second Industrial Revolution – radio, the telephone, the internal combustion engine, air travel, etc. were clearly dependent on modern science in a way that the spinning jenny and the steam engine were not. And it is inconceivable that someone without biological training could play an important role in the bioengineering that is already starting to produce the major innovations of the 21st Century.

Thus the biotechnology revolution is increasing the complementarities that have always existed between science and technology. They are therefore also increasing the mutual interdependence between universities and industry, and making the role of universities in the growth process even more critical than before. Future growth will call for innovations in biotechnology, which will take place most readily if biotechnological development is done in concert with progress in fundamental biological sciences. Healthy universities that support the biological sciences and promote interactions between biotechnology and biology are needed for this to occur.

7. The challenge facing universities

Some maintain that increased commercial involvement with universities is fundamentally incompatible with the values of a university and the ethos of science, that universities should stop compromising the culture of open science and stop promoting the production of patentable innovations. I guess I have made it clear from what I have said already that I don't think such an attempt to insulate universities from private enterprise would be good for universities, for science or for economic growth. In any event I think the biotechnology revolution is making it inevitable that universities will be entering into more partnerships with private enterprise. It is already driving up salaries for highly qualified scientific personnel, thus presenting universities with escalating salary demands that they are going to have to meet in order to keep fulfilling their mission of supporting the life sciences. As fiscal pressures make governments less and less willing to promote scientific research I believe universities will be driven to take advantage of the huge potential profits from patentable research and from sponsorship by business partners, in order to meet those increased salary demands. Indeed we are already seeing universities encouraging faculty to seek patents, and allowing their top biologists to maintain a private laboratory on campus just in order to keep them from leaving.

The increasing synergies that we can see between science and technology imply that increasing commercial involvement with universities can also benefit the course of science, by facilitating the sort of interaction between theory and experience that has so often in the past led to fundamental scientific breakthroughs. In addition, the potential profits of biotechnology give universities an opportunity not only to foster better science but also to fulfill their broader academic mission of fostering the arts, the humanities, and other activities that are essential to university life but have little direct commercial value, by subsidizing research and teaching in these areas using the revenues they earn through the patent system.

I agree however that increasing the involvement of private commercial interests in university life carries with it some serious risks to universities and to open science. To a large extent this is because the ethos that supports open science conflicts in many ways with the commercial values of private enterprise. In particular, the privatization of knowledge that is second nature to commercial enterprises, who rarely share except when forced to by disclosure requirements, is anathema to academic life. If universities do not insist on the right of all faculty members to publish freely the results of any research engaged in as part of any joint venture or partnership with outside interests, they will be undermining the culture that has made open science such a flourishing enterprise and such a force for good.

Another serious risk is that universities might allow commercial motives to distort their priorities. This is the other side of the opportunity to subsidize the arts and humanities. As academic administrators realize how much money they can earn from promoting patentable research they will inevitably be tempted to start running universities more and more on business principles. In fact we are already starting to see this, with "accountability" and money-raising playing an increasing role in intra-university resource allocation. As this happens I fear that fewer resources will be allocated to those parts of the university unable to generate pecuniary revenues, that is to those parts that ought to be subsidized by the parts that *can* generate revenues.

Yet another risk is that as more power within the university is acquired by scientists leading lucrative research projects, pressure will be increasingly applied on students and junior faculty to engage in routine research directed towards the goal of such projects rather than to engage in more scientifically valuable lines of investigation. Coercion by senior faculty is always a threat to a healthy academic environment, and it seems to me inevitable that the biotechnology revolution will intensify that threat.

As Ziman points out, the tendency to run universities more and more like businesses is inducing scientists to seek resources in an increasingly "competitive" university environment by engaging in "entrepreneurship", the kind of behaviour that conflicts directly with the disinterestedness imperative of CUDOS. Many researchers simply aren't cut out for that kind of competition. Indeed it is the inability to compete, except in the world of ideas, that drives many into academic life. Many scientists, indeed probably the best, really are driven by curiosity, not by the quest for empire or profit, and such people find it an increasing drag on their time and energy to be forced to engage in the puffery of grant applications, activity statements and the like.

So the big challenge facing universities at the start of the millennium is to find a way to take advantage of the opportunities opened up by the biotechnology revolution without sacrificing academic values and the culture of open science. This culture is a precious heritage of social evolution, which cannot be sustained by market forces alone. It needs the support of strong universities. The biotechnology revolution holds out the promise of providing universities with the resources needed to remain strong in the face of rising costs and shrinking public support. But only if they engage increasingly with private enterprises whose interests and values conflict with the ethos that underlies open science.

I believe that past experience shows that universities are capable of rising to that challenge. In the United States after World War II, when federal money started pouring into universities in support of scientific research, much of that money came from agencies, especially the Department of Defense, who, like private enterprises, have a vested interest in secrecy. As Kennedy (1996) has observed, the Pentagon initially tried to retain the option to deny publication rights to university researchers working on projects it was sponsoring. Indeed it even took universities to court on occasion. But by and large American universities held to their principles, and the Pentagon had to give in, except in the case of pure contract research. Instead of contributing to the demise of open science, American universities used the opportunity of this increased funding to become world leaders in almost all branches of science during the half-century following World War II.

Universities have the bargaining power to take the same stand against private interests today, and to resist the pressures to undermine the culture of open science. Their bargaining power comes from what they have to offer their industrial partners. In exchange for money and the opportunity to get involved in the development of leading-edge technology, universities can offer access to the scientific community, a community that only they can nurture and protect. In a world where such access is becoming increasingly vital to the success of technological development, that bargaining chip is becoming increasingly valuable. I believe that it holds the key to a successful future for universities, and also the key to continued economic prosperity.

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