COUNTY
Investment Management

THE BIOTECHNOLOGY REVOLUTION:

A UNIQUE OPPORTUNITY FOR AUSTRALIA*

N D Birrell
Chief Executive

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*This paper results from research undertaken as part of County's investment process in which we assess the impact on markets of major structural changes in society and the economy.

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Prologue

Put yourself forward in time 100 years. You are a 130 year-old athlete, and have just run your best time in the annual over-120s marathon. Last week you visited your local DNA Bank to replace a couple of limbs that were beginning to feel worn out, after some annoying compatibility problems you experienced after your second artificial heart transplant three years ago. Your diet for today includes the latest cloned cholesterol-free beef and genetically-engineered tomatoes, which were developed in the laboratory of locally-based conglomerate FlexiVeg Incorporated. Fortunately you have sufficient financial resources to pay for this indulgent lifestyle because you live in Australia, the centre of the world's biotechnology industry for the past century.

Does this all sound fanciful to you?

It is the contention of this paper that, on the contrary, the scenario described above is not only plausible, but is likely to be quite commonplace in the world to be inherited by our children - or perhaps (if we are very fortunate) to be achievable within our own lifetimes. The catalyst for this brave new world - and for the immense social changes, economic impacts and moral dilemmas it will bring - is the impending revolution in biotechnology research, a revolution which has the potential to unleash structural changes more profound than any technological advance in human history.

While the biotechnology revolution will pose many challenges, both practical and ethical, to all nations, Australia has the opportunity not only to rise to these challenges, but also to prosper from them. With some vision from Government, providing a suitable policy environment, and from business, in grasping the opportunity, Australia has the opportunity to be at the centre of "Genome Valley", the 21st century equivalent of today's icon of successful technological development, Silicon Valley.

Achieving such an outcome is the topic of this paper.

1 The biotechnology revolution

Much has been written on the biotechnology revolution, with interest being particularly heightened last year with the announcement of the cloning of the sheep named Dolly[1].

As with most scientific revolutions, the biotechnology revolution has evolved from many small steps interspersed with some giant leaps. The historical timeframe of developments in biotechnology can be set by the date of three significant leaps.

1. The first is the discovery of the three-dimensional, double helix structure of DNA by Watson and Crick in 1953. The structure of DNA encodes all of the genetic information of life. In a sense, Watson and Crick started the process of decoding the equivalent of the computer program that determines the nature of each life form.

2. A further major leap forward occurred in 1973 when Cohen and Boyer performed the first successful recombinant DNA experiment. Recombinant DNA technology allows pieces of DNA from one source to be recombined with DNA from another source. This technology is not only used for developments such as the cloning of Dolly but also for the development of genetically engineered drugs and as a tool in the ongoing search for the understanding of the genetic structure of life.

3. It was with this latter intent in mind that a further major step forward was initiated in 1988, with the launch of the human genome project[2]. The aim of this 15-year project, funded by the United States Department of Energy and National Institute of Health, is to determine the complete chemical structure of human DNA and to locate the estimated 50,000-100,000 genes within the human genetic structure. In effect, the project is aiming to complete the decoding of the program of life.

Already, the human genome project is helping to identify genes associated with diseases, thus allowing research into therapies[1]. In the early part of the next century, the flow-on effects of the project and associated technology will snowball, with profound implications for societies and economies.

Rather than speculate on specific applications and implications, we attempt to highlight the magnitude of the structural change that will be wrought by the biotechnology revolution by drawing on an analysis used to elucidate the impact on the US economy of the information technology revolution.

[1] See "The Biotech Century", *Business Week*, March 10, 1997, Page 36.
[2] For an overview see the World Wide Web link of the National Human Genome Research Institute: www.nhgri.nih.gov/HGP/

The paper[3] reproduced in Appendix A sets out to resolve the following paradox:

The United States has maintained a fairly constant productivity lead over Japan and Germany despite having a savings/investment rate which was not only the lowest for three decades, but which declined sharply throughout most of the period as well.

The paper explains this paradox by arguing that the United States' mastery of information technology so increased its "innovation quotient" as to compensate for the impact of declining savings. The reason that information technology was able to have this effect is that it is a so-called General Purpose Technology (GPT)[4]. The concept of a GPT is discussed on page 10 of Appendix A. It is recommended that the reader should read that discussion or, ideally, all of Appendix A before proceeding.

The paper in Appendix A argues that binary logic and electronic circuits (the heart of information technology) are today's GPT. The general-purpose nature of the technology is what has led to information technology having such a profound economic structural effect.

The structural logic of DNA and recombinant DNA technology (the heart of biotechnology) are likely to be the GPT of the 21st century. The special characteristic of this GPT is that it is the technology of life. As a consequence, the impact of this GPT is likely to be more profound than any before[5].

Mastery by a country of the GPT of biotechnology is bound to result in an accelerating innovation quotient, just as in the case of information technology. The domination of aspects of information technology, such as Microsoft's dominance of PC operating systems with its Windows product, is to some disturbing[6]. Domination by countries or companies of the GPT of biotechnology will bestow power that will make the information technology domination issues seem insignificant.

The granting of patents over biotechnological discoveries is facilitating the potential for domination. The logic for awarding patents in biotechnology is exactly as for other areas of innovation. The difference, that has caused controversy, is that patents are being awarded over fundamental elements of life.

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[3] This analysis is inspired by an August 1995 report from Strategic Economic Decisions Inc., reproduced as Appendix A, with their kind permission.

[4] See Appendix A and "General Purpose Technologies: Engines for Growth?", T Bresnahan and M Trajtenberg, National Bureau of Economic Research, Working Paper No. 4148, 1992.

[5] Previous General Purpose Technologies, apart from electronic circuits, include printing and the steam engine.

[6] See, for example, "Court warns off 'bully' Microsoft", *The Weekend Australian*, December 13-14, 1997, Page 16 or "Justice vs. Microsoft: What's The Big Deal", *Business Week*, December 1, 1997, Page 63.

An interesting review of this controversy can be found in a paper by McNally and Wheale[7], in which the authors propose that biotechnology patents will lead to significant structural change, which they characterise as follows:

Biotechnological innovation constitutes a new "regime of accumulation" while the globalisation of intellectual property rights in genetically engineered life forms constitutes a new "mode of regulation". The combination of the two is creating a new global order dominated by the bio-industrial complex.

Much of the remainder of this paper is concerned with Australia's place in this new global order.

[7] "Biopatenting and biodiversity: comparative advantages in the new global order." *The Ecologist*, September 1996, Page 222.

2. Lessons for Australia

Cries of lack of government "vision" have become familiar in Australia in recent times, resulting in the Prime Minister's policy statement "Investing for Growth"[8]. Be they associated with high unemployment or the need for industry policy, we believe that the root cause of these pleadings is the perception that Australia is ill-prepared to deal with the massive structural change that is currently sweeping the world.

Change, generally labelled as "globalisation"[9], can be seen as exporting Australian jobs, increasing unemployment, and as intensifying the corporate competitive environment, resulting in calls for industry policy.

The massive structural change to an "information economy" in the developed world can be seen as sweeping past Australia, leading to massive opportunity in the United States and some other countries[10].

National benefit from structural change does not occur solely by chance. Planning by government and industry in anticipation of the impact of structural change can have a dramatic effect on whether a country is a winner or loser from change.

The strong position of the United States in information technology arguably stems from the hundreds of billions of dollars of U.S. Government expenditure on information technology research and development as a result of the space and arms races[11]. The United States Government foresaw the change that would result from such technology admittedly, in very narrow fields. This investment has spilled over into myriad related fields giving the United States unrivalled superiority in commercial information technology.

The Australian Government's initiatives to catch up in information technology[8] are admirable but are 40 years too late to capture the most high value advantage. This is the time that it has taken Silicon Valley to develop from its roots to the information technology powerhouse that it is today[12] [13].

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[8] The statement is available on the Internet at www.dist.gov.au/growth. See also "Going for Growth: Business Programs for Investment, Innovation and Export", D Mortimer, Commonwealth of Australia, June 1997.

[9] "Globalisation vs Tribalisation: A County Theme for the 90's", *County InHouse*, County NatWest Investment Management, August 1995.

[10] "The Global Information Economy: The Way Ahead", The Information Industries Taskforce, Professor A Goldsworthy, Chairman, Commonwealth of Australia, July 1997.

[11] United States Budget for Fiscal Year 1996, Tables 9.7 & 9.8

[12] "Silicon Valley: How it really works", *Business Week*, August 18, 1997, Page 46.

[13] "Survey: Silicon Valley", *The Economist*, March 29, 1997, Page 66.

Australians should be asking how are we going to be at the centre of the "Silicon Valley" of the next revolution. This requires looking to the structural changes that are likely to have profound global repercussions early in the next century, rather than just attempting to catch up with the structural changes of the past.

The biotechnology revolution offers many opportunities for a nation prepared to embrace the change to its advantage. Australia is fortunately well positioned to benefit from the biotechnology revolution.

3. SWOT analysis

To take a systematic approach to forming an appropriate response to such change, we undertake an analysis of Australia's Strengths, Weaknesses, Opportunities and Threats (SWOT) in relation to the biotechnology revolution.

3.1 Threats

We start with threats to get the potential bad news out of the way.

The primary focus of this paper is the economic impact of the biotechnology revolution and the social consequences that flow from the economics. We thus do not consider the potential ethical and related social consequences of the revolution, although these pose many threats that certainly require considerable attention.

The economic threat from the biotechnology revolution is primarily to our balance of trade. The structural changes described in the previous section will lead to an increasing proportion of our consumption being in goods and services that result either directly or indirectly from the GPT of biotechnology.

Australia's poor position in transitioning from the agrarian age to the post industrial revolution era[14] and from that era to the information age has left us with a structural balance of payments deficit[15] and Australian jobs being "exported" overseas. As we move to the biotechnology age the threat of this trend continuing looms large.

Two additional structural effects magnify the threat. The first is globalisation, referred to earlier in this paper. In the world of global free trade of the 21st century, Australia will not be able to hide behind the tariff barriers that it has used to protect itself in previous transitions. Such trade protection has arguably left Australia in a worse position at the end of the transition by allowing Australia's business and government leaders to push on without a clear vision of Australia's place in the changed world. This protection will not be available in dealing with the transition to the biotechnology age. Vision will be required

[14] In the 1800s, Australia had the World's highest GDP per capita according to an OECD study "Monitoring the World Economy 1820-1992", OECD 1995. By 1992, Australia had fallen to 13th in the sample of 56 countries in the OECD study. See also, "The century the earth stood still", *The Economist*, December 20, 1997, Page 65.

[15] In 1994-95 Imports of Computer Merchandise, Services and Royalties were valued at $5,97 billion compared with exports of $1.73 billion. The deficit of $4.24 billion was a 16% increase on 1993-94. ("Balance of Payments and International Investment Position. 1994-95", Australian Bureau of Statistics.)

The second structural change is demographic. The Australian population is ageing, with the baby-boom demographic bulge passing into late middle age. For example, it is forecast[16] that the median age of the Australian population in 2031 will be 41.2 years, compared with 33.7 years in 1995, and that 20.7% of the population will be aged 65 or over, compared with 11.9% in 1995.

Since spending on health care tends to rise with age, this demographic structural change is expected to result in significantly increased health care expenditure[17 18].

Apart from demographics, technological change is thought to be one of the most significant factors affecting health care expenditure[18 19]. The massive structural change resulting from the rapid development of the GPT of biotechnology combined with the significant forecast ageing of the population makes forecasting of future health care expenditure as a percentage of GDP a most hazardous business.

Careful forecasts of health care expenditure in the United States using both actuarial and macroeconomic approaches show costs rising to anywhere from 25-50% of GDP depending on assumptions[20]. Whilst Australia is coming off a lower base of expenditure than the US (8.8% versus 14.0% in 1992), the impact of the structural changes discussed here is likely to be similar.

The threat to Australia of becoming increasingly dependent on the largely foreign controlled bio-industrial complex, referred to in the previous section, is thus particularly acute in the health care sector. The growing aged percentage of the population will increasingly demand access to the medical wonders wrought by biotechnology and woe betide any politician that stands in their way.

The area of agricultural biotechnology also represents a huge potential threat to Australia, with Australia's farm produce and resultant exports becoming increasingly dependent on biologically engineered seeds and related chemicals manufactured overseas.

[16] "Projections of the Populations of Australia States and Territories", Australian Bureau of Statistics publication 3222.0

[17] "Economic perspective on the health impact of the ageing of the Australian population in the 21st century", Paper presented on 23 September 1994 at the Seventh National Conference of the Australian Population Association at the Australian National University, J Gross, S Eckermann, M Pinyopusarerk, X Wen.

[18] "Health Care Reform – Controlling Spending and Increasing Efficiency", H Oxley and M MacFarlan, OECD Economics Working Paper No. 149, 1994

[19] "Can the NHS cope in the future?", A Harrison, J Dixon, B New, K Judge, British Medical Journal, November 1997, page 139.

[20] "Projections of health care expenditure as a share of GDP: actuarial and macroeconomic approaches.", M Warshawsky, Health Services Research, page 293.

The economic stress point of this threat is Australia's balance of payments. Australia already runs a large and growing balance of payments deficit as a result of its dependence on the rest of the world for the current GPT, namely information technology[15]. The medical, life and food related aspect of biotechnology greatly amplifies the threat of external dependence on next century's GPT.

3.2 Strengths

Australian has a remarkably strong starting point from which to benefit from the biotechnology revolution.

Before turning to immediately relevant strengths, it is worth taking a "big picture" view of Australia's strengths in Science and Technology. For this we turn to the "World Competitiveness Yearbook"[21]. This publication brings together for 46 countries a large number of factors that impact on a country's competitive position. Australia ranked 18 out of 45 in overall competitiveness. In the category of Science and Technology, Australia 's highest rankings are:

Number of patents in force:	10/46
Total expenditure on R&D:	12/46
Nobel Prizes	12/46

In the specific area of medical research, Australia has an outstanding track record[22]:

Australia's health and medical researchers produce about ten times more knowledge than would be expected for the size of our population and the money invested. We have had three [now four] Nobel Laureates in medicine and our scientists regularly win the world's most prestigious research awards.

Australian health and medical research is also very well organised. Dr John Bienenstock, Dean and Vice President of the Faculty of Health Sciences at McMaster University, who conducted an external review of the NHMRC is quoted as saying of the NHMRC[23]:

[21] "World Competitiveness Yearbook", IMD International, Switzerland, 1997.
[22] "Towards a Strategic Plan for the NHMRC: June 1995 to December 1996",National Health and Medical Research Council, 1995.
[23] *Annual Report of the NHMRC*, 1996, Page 8. The Annual Report also gives an excellent overview of the operation of the NHMRC and some of the outstanding research funded through its auspices. See also "Report of an External Review of the National Health and Medical Research Council", J Bienenstock, December 1993.

It is unique to this country that one organisation can have a remit that extends over the full field of health, and which includes responsibility for supporting and developing health research. This organisation can harvest the knowledge and goodwill of Australia's foremost experts at minimum cost, to provide governments and the community with comprehensive and authoritative advice on a host of complex issues which affect the nation's health.

Australia's history of well organised support for medical research has led to the development of a wealth of world leading research centres and institutes, a number of which have produced work at the leading edge of the biotechnology revolution.

Research success in these organisations has led to the development of a small Australian medical technology industry. The Healthcare and Biotechnology sector of the Australian Stock Exchange currently lists 37 companies[24], a number of which are conducting research at the forefront of the biotechnology revolution[25]. Most of these companies are quite small and not well established.

A great strength is the close cooperation between Australian Universities, Research Institutes and companies aiming to exploit biotechnology research. Cooperative Research Centres (CRCs) provide a government sponsored forum for such cooperation. For example, the CRC for Discovery of Genes for Common Human Diseases brings together listed biotechnology and pharmaceutical company AMRAD with the Walter and Eliza Hall Institute of Medical Research, the Murdoch Institute, the Queensland Institute for Medical Research and the Centre for Molecular and Cellular Biology of the University of Queensland.

Commercial arrangements between biotechnology companies and research institutes are also common. For example, the listed biotechnology company BioDiscovery has joint venture arrangements with The John Curtin School of Medical Research, CSIRO Entomology, The Garvan Institute of Medical Research and the Cytokine Unit of the University of New South Wales. Another fine example is the research commercialisation relationship which AMRAD has with ten of Australia's health and medical research institutes, which are also shareholders in AMRAD.

The strengths and environment described above are reminiscent of those existing in information technology in the early days of Silicon Valley. The opportunity for exploiting these strengths is considerable but they are countered by some major weaknesses which have the potential to prevent Australia realising a 21st century success similar to that of the US in information technology in this century.

[24] *Australian Financial Review*, p51, 22-23 November 1997.
[25] For some more information of Australian biotechnology organisations see the Internet site of the Australian Biotechnology Organisation at www.abn.asn.au

3.3 Opportunities

Australia's strength in medical research and biotechnology, positions it well to neutralise the threat described in section 3.1. It also provides Australia with the opportunity to build a stronger, diversified economy by being a leader in the GPT of the 21st century.

This opportunity has not been lost on other countries. The following is the executive summary of a supplement to the United States President's Fiscal Year 1994 Budget, which included a 1994 Biotechnology Research budget of US$4.3 billion[26]:

Biotechnology is a burgeoning industry worldwide, and analysts are predicting that it will have a profound impact on health care, agriculture, energy, and environmental management. By the year 2000, the biotechnology industry is projected to have sales reaching $50 billion in the United States. Development and production of biotechnological products will create thousands of new jobs and promote renewed economic growth, and has the potential of helping address agricultural, environmental, and health concerns in developing countries.

Biotechnology-related industry in the U.S. is characterized by very close linkage to its research base. Over the past three decades, with basic research support from the Federal government, the United States has become the international leader in biotechnology research, development, and commercialization. Increasing competition, however, has caused the United States' leadership in biotechnology to diminish.

Recognizing the profound impact biotechnology will have on society and the fragility of the U.S.'s position in this rapidly growing sector of the global economy, the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) selected biotechnology research for special emphasis in the FY 1994 Federal budget. The goal of the Federal Biotechnology Research initiative is to sustain and extend U.S. leadership in biotechnology research for the 21st century, in order to enhance the quality of life for all Americans, and to spur the growth of this important component of a healthy U.S. economy.

With the United States already having a dominant position in biotechnology and being determined both in the government and corporate[27] sectors to maintain that dominance, is it worth Australia trying to compete?

[26] "In the National Interest – Biotechnology for the 21st Century: Realizing the Promise", A Report by the Committee on Life Sciences and Health of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET).

[27] One of the most determined US corporates in this regard is Monsanto, which presents a fascinating case study of the opportunities and resultant threats of the biotechnology revolution. See "Bucking biotech: the global threat of the new agribusiness.", K Dawkins, *Dollars and Sense*, May 1997, Page 26.

Within the global trade and business environment envisaged in the 21st century, the notion of countries competing against one another is an ill-defined concept. Biotechnology is likely to be dominated by a relatively small number of transnational corporations, in competition against one another. The correct question to ask is how can Australia prosper in such an environment.

The answer is to vigorously nurture the intellectual capital that provides so much of Australia's strength in medical technology and to rigorously protect and exploit the intellectual property that results from the wise application of this intellectual capital.

The opportunity to undertake the second part of this prescription is provided by the very intellectual property protection mechanisms that are a potential element of the threat discussed in section 3.1[7].

The global nature of the biotechnology industry, developments in information technology[28] and the intellectual property rather than goods nature of the above prescription mean that Australia's geographic location is not the disadvantage that it has been in past endeavours. Indeed, Australia's geographic proximity to the developing Asian region provides a great opportunity for the export of Australian medical technological expertise and product.

Apart from demographics and technology, as discussed in section 3.1, a particularly important factor affecting demand for health care is household income[18]. As incomes rise in the developing regions to Australia's north, health care expenditure as a percentage of GDP is also expected to rise. Much of this expenditure, especially on new technological developments, will be on imports. Australia should be well positioned to fill some large part of this demand.

A similar argument applies to nutritional needs. The continued development of Australia's northern neighbours is expected to greatly increase demand for food[29]. This demand is unlikely to be easily satisfied without ongoing biotechnological improvements to food production. Australia is well placed to supply much of this additional demand and to benefit greatly, provided it is not simply the provider of the soil and labour with the major benefits going to the foreign bio-industrial complex discussed previously.

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[28] The Internet is playing a major role in the development of biotechnology and, in particular, the Human Genome project. A good starting point for browsing is the Human Genome Project World Wide Web site of the Oak Ridge National Laboratory of the United States Department of Energy at www.ornl.gov/TechResources/Human_Genome/home.html

[29] See, for example, "Global Food Projections to 2020: Implications for Investment", M W Rosegrant, M Agcaoili-Sombilla and N D Perez, International Food Policy Research Institute, Food, Agriculture and the Environment Discussion Paper 5, October 1995.

One of the particularly appealing aspects of a general-purpose technology as a driver for economic development is the spillover effect of the technology into myriad industry sectors[4]. The extraordinary economic growth generated in Silicon Valley[30] by the GPT of electronic circuits may well be replicated in some locales in the 21st century as a result of the biotechnology GPT.

Some cities and regions in the United States are already seizing this opportunity[31]. Australia's strengths in medical research and technology, highlighted in section 3.2, provide a great opportunity for a State Government to put in place an initiative to establish their capital city as the centre of a 21st century "Genome Valley". Some of the means by which this opportunity might be exploited are explored in section 4.

3.4 Weaknesses

Many perceived weaknesses holding back Australia's industrial development have been implicitly or explicitly described in various reports into aspects of Australian Industry[32]. Such weaknesses clearly affect Australia's ability to seize the opportunities presented in the previous section and make us more vulnerable to the threats described in section 3.1.

Rather than simply reiterate the weaknesses highlighted in these reports, a more challenging approach is adopted here based on a most insightful analysis entitled "Vital intangibles" in the Economist survey of Silicon Valley[13]. The article commences: *Imagine yourself as one of those many foreign bureaucrats now charged with trying to build Silicon Valleys of their own…As you wend your weary way from Sand Hill Road to Stanford University and San Jose, you ask yourself: "Why did it happen here?"*

Asking, "Why would it not happen here?" provides a means of exploring Australia's weaknesses with respect to the present topic. The Economist article provides food for thought:

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[30] The GDP of Silicon Valley's 2 million inhabitants is estimated to be US$65 billion (see reference 10). By comparison, Australia's GDP, with about 18 million people, is about US$350 billion. Silicon Valley is home to around 7,000 electronics and software companies, with 11 startups being created every week. Between 1992 and 1996 125,000 new jobs were created in Silicon Valley. In 1996 62 new millionaires were created every day and real wages grew 5.1%, five times the national average. (See reference 6.)

[31] For example, see "San Diego's emerging 'DNA Valley' needs careful nurturing", E Shneour, The San Diego Union-Tribune, 13 August 1996, Page B-5 and "Special Feature: Biovision 2000: Growing Bioscience across North Carolina", *BT Catalyst*, June 1997.

[32] See, for example, references 8 and 10 and, specifically related to Science, see "A report to the Minister for Science and Technology, on Arrangements for Commonwealth Science and Technology", by the Chief Scientist, Professor John Stocker, Canberra, June 1997

Until recently, economists and politicians would put Silicon Valley's success down solely to a handful of good, solid reasons: the size and flexibility of its labour pool, the breadth of its network of suppliers, its access to venture capital and the excellence of its educational facilities and research institutions...

Research has increasingly concentrated on clusters-places (such as Hollywood or Silicon Valley) or communities (such as the overseas Chinese) where there is "something in the air" that encourages risk taking. This suggests that culture, irritatingly vague though it may sound, is more important to Silicon Valley's success than economic or technological factors. Here is a list of what it takes:

The article then goes onto elaborate on the following factors:

Tolerance of failure
Tolerance of treachery
Risk-seeking
Reinvestment in the community
Enthusiasm for change
Promotion on merit
Obsession with product
Collaboration
Variety
Anybody can play

The article concludes under the sub-heading ***Masterful inactivity***:

For would-be imitators of Silicon Valley, this list might not look altogether helpful. First, some of the required attributes seem somewhat ill defined (how would you explain the importance of "the cool idea" to an Asian autocrat?). Second, the list as a whole seems to imply that government has had little role to play in the valley's development. That conclusion would be wrong, but for reasons that are more complicated than they might at first appear.

A few people still believe that Silicon Valley was built by the American government. By one count, in the period 1958-74 the Pentagon paid for $1 billion-worth of semiconductor research. The Internet, too, began as a government project; several companies, including Netscape, have arisen, directly or indirectly, from state-funded research projects. Even today, 10% of Xerox PARC 's budget comes from the American government.

However, there is a clear difference between being a big customer and calling the shots. On only one occasion--in the mid-1980s, when the memory-chip industry was overrun by suspiciously cheap imports from Japan--has Silicon Valley gone to Washington for help; many in the valley still view the resulting Semiconductor Trade Agreement with shame. The prevailing attitude nowadays is that governments--however well-meaning--should stay well out of it.

Yet the conclusion that Silicon Valley is a government-free creation is surely wrong. If nothing else, the American government has made a powerful contribution by not doing things that would have messed it up. Just look at Europe, where a twin policy of maintaining high semiconductor tariffs and bailing out high-tech firms has helped to reduce the region's share of the world market for "electronic data products" (which includes computers) from 23% in 1988 to 18% in 1996. In Silicon Valley, success in just about any area turns out to hinge on either some liberalising legislation, or the absence of any legislation at all.

Two easy examples are America's bankruptcy laws and California's tax structure, which has historically treated capital gains more generously than income. But there are other, more fiddly ones. Ron Gilson, a professor at both Stanford and Columbia law schools, points out that Californian law, unlike its Massachusetts equivalent, regards "post-employment covenants not to compete" as unenforceable. That makes it much harder to tie down staff. On the other hand, American law is relatively tough on patents: if a firm has an idea, it can protect it.

As the Economist article points out, many of the factors listed above are ill defined. This is because they have much to do with culture, which cannot easily be analytically dissected nor quantified. From an examination of a combination of anecdotal evidence and hard fact, it is however, possible to draw the conclusion that Australia does not sit well with respect to many of these factors.

For example, consider the first factor, "Tolerance of failure". The much discussed, but anecdotal, "tall poppy syndrome" indicates that Australians, rather than tolerating, take a perverse delight in the failure of "high flyers". Also, the hard fact of Australia's bankruptcy law is that it is difficult for Australian bankrupts to start a business, while many of Silicon Valley's greatest successes have been former bankrupts.

One common thread through most of the factors is the attitude of management. This has been studied systematically in the Karpin Report[33]. A more anecdotal review is found in a recent book by Ivan Deveson[34]. Both publications observe significant challenges for improvement of Australian management, many of which relate to the factors above.

One theme common to both publications is the need for Australians to become more entrepreneurial. This weakness is evident in the "World Competitiveness Handbook", used in section 3.2 to note some of Australia's strengths. "Entrepreneurship and innovation" is certainly one of Australia's weakest factors, ranking 28/46.

[33] "Enterprising Nation – Reviewing Australia's Managers to Meet the Challenges of the Asia-Pacific Century", Australian Government Publishing Service, 1995.
[34] "Evolution of an Australian Management Style", I Deveson, Business and Professional Publishing, 1997.

The Handbook can also shed some light on Australia's relative position with respect to other factors cited above. For example, Australia ranks 22/46 on Financial Resources for Technological Development, 31/46 on Venture Capital and 40/46 in response to the survey question as to whether "relocation of R&D facilities is a threat to the future of the economy". Further, while ranked reasonably at 16/46 on "Basic Research", Australia ranks behind countries such as New Zealand, China and Malaysia.

While these weaknesses are largely those of the private sector, the Australian Government has certainly not been "masterfully inactive", in the sense of The Economist review. While the current government has a commitment to the reduction of red tape and bureaucracy standing in the way of the development of small business, only minor inroads have been made to date[35]. On an international competitiveness basis, however, Australia's government bureaucracy is not too bad, ranking 17/45.

Australia's worst government competitiveness factors are:

Personal income tax:	39/46
Capital and property tax revenues:	39/46
Corporate Taxes:	36/46
Labour regulations:	34/46

Internationally non-competitive capital gains tax is often cited as a major impediment to the development of a high-technology sector in Australia.

When compared with the US Government's contribution to semi-conductor research, the Government must bear some responsibility for Australia's poor competitive position in Financial Resources for Technological Development.

A danger of the recent lobbying for a more interventionist industry policy is that the government will become un-masterfully active. This danger was emphasised recently in a presentation by the President of the National Competition Council, Graeme Samuel[36].

[35] "Canberra blamed for failure to untangle red tape.", I Henderson, *The Australian*, Page 6, 15 October 1997.
[36] "Leadership in Business and Government – Keeping Reform on Track", G Samuel, National Competition Council, November 1997.

4. Reaping the benefits

The preceding sections have argued that the biotechnology revolution will cause massive structural change, posing considerable threats and enormous opportunities for Australia. What needs to occur for Australia to grasp the opportunities and reap the benefits of the revolution?

In summary form, the process that will lead to the generation of national wealth from biotechnology runs like this:

i) Australian scientists perform world class basic research in a well funded, supportive environment with access to state of the art infrastructure. The nature of biotechnology as a GPT means that unpredictable discoveries are likely to be made. Scientists should have the opportunity to explore avenues that may not lead to commercial research, without fear of "failure". Such an environment will help to retain the best intellectual capital in Australia.

ii) Basic research is undertaken in a commercial framework that ensures that resultant valuable intellectual property will either stay in Australian ownership or will be commercialised in a manner that will generate appropriate economic benefit for Australia.

This objective is met by an entrepreneurial private sector working closely with basic research organisations, unhindered by government obstacles and incentivised by the aim of financial reward appropriate to the risk and not inappropriately reduced by uncompetitive government taxes.

iii) By the nature of a GPT, once a critical mass has been reached the economic benefits "snowball", creating wealth in diverse areas of the economy.

As has been discussed in section 3.4 under "weaknesses", there are various impediments to achieving this vision.

The "cultural" impediments will take time to change. Some of the proposals of the Karpin Report[45] are thought likely to assist in bringing about such change. There is also great opportunity for governmental support for cultural change. Such assistance need not be primarily of a monetary nature but rather involve providing moral support for cultural change.

In this regard, there is an especially good opportunity for a State Government to take the lead in providing the cultural and infrastructure environment for the development of a "Genome Valley". The "clustering" effect referred to in the Economist article in section 3.4 would appear to give Melbourne, with its heavy concentration of medical research and biotechnology companies, front running in achieving such an outcome.

Both Federal and State Governments need to concentrate on removing impediments to the process above. Tax reform, especially to capital gains tax, is seen as a vital ingredient to encouraging innovation and investment in high-risk research.

We have seen that financing of technological development and venture capital funding are two of the significant weaknesses standing in the way of the wealth generation process above. The Australian venture capital industry is quite immature[37] and while Government initiatives such as the R&D Start program and Innovation Investment Fund are to be applauded, the funding pales into insignificance when compared, for example, to the $US4.3 billion U.S. budget allocation to biotechnology referred to in section 3.3.

The financing of medical biotechnology research through to the point of human application can be enormously expensive and take long periods of time[38]. As a result, Australia does not have the financial resources to take many of its basic research innovations through to final application. For this reason, much Australian biotechnology intellectual property is being sold to overseas owners or is being developed in joint ventures between Australian and overseas companies[39]. While there is no fundamental problem with such international cooperation, it is vital that Australian biotechnology R&D institutions and companies are sufficiently well funded to negotiate arrangements that favourably protect their intellectual capital and bring a significant share of the economic benefit of their innovations to the Australian economy.

What is the appropriate source of funds to finance Australia reaching the critical point, referred to in iii) above, from which it will enjoy the economic benefits of the biotechnology revolution?

The appropriate way in which to address this question is to answer the question "who will enjoy benefits referred to?"

In answering this question, it is necessary to recognise that the investments required in both steps i) and ii) above are of a long-term nature. Basic research can proceed for many years without turning up radical innovations and then, as mentioned above, the road from discovery to commercialisation can take many further years.

The benefits of basic research can thus be intergenerational. That is, research being funded by the current generation may only payoff for subsequent generations. It is for this reason that basic research is substantially publicly funded, with one of the purposes of government taxes being to invest intergenerationally[40].

[37] For a review see *The Australian Financial Review,* 3 December, 1997, Page 39.
[38] Time and cost of phase 3 trials etc.
[39] See, for example, "Australia's Role in Product Development", *Health Care Herald*, Page 2, Burdett, Buckeridge & Young, October 1997.
[40] In the United States, significant amounts of money are also invested by the private sector on basic research in the belief that this will lead to shareholder benefits. See "Mr Gates Builds His Brains Trust", *Fortune*, page 62, 8 December 1997.

The ageing of the population and the resultant expected increase in health expenditure referred to in section 3.1, provides a further reason for the government to invest heavily in biotechnology research. The government will undoubtedly be paying a large part of the growing future medical expenditure. Australia is still in a position from which it can aim for this growth to be self funded through economic growth associated with the new GPT. If we fail, then the expenditure growth will inexorably lead to an increase in our international indebtedness.

The Australian Society for Medical Research proposes that an appropriate budget allocation to medical research is 5% of total health expenditure[41]. This would involve doubling direct government support for NHMRC-administered peer-reviewed grants. The arguments of this paper strongly support such a proposition. Indeed, to ensure that Australia reaches the critical point referred to above, a major initiative such as that in the U.S. is supportable.

It should be noted that such an initiative is not the same as government industry support as condemned in the previous section. Such an initiative should be seen as primarily involving the bringing forward of inevitable government expenditure as investment rather than recurrent expenditure, with the desired aim of reducing total future government expenditure as a proportion of GDP. It also differs from proposed industry support schemes in that it need not directly benefit the shareholders of private sector companies.

As individual members of the ageing population will also benefit from advances in biotechnology and will be exposed to the costs of these advances, it is particularly appropriate that individuals make suitable investments to mitigate this liability. As much of the benefit and cost will be seen in the latter years of their lives, in retirement, it is especially appropriate that individuals' retirement savings take account of this expected growing liability.

For individuals with a long time to retirement, the long lead times for investment in the process above should not be seen as a barrier. For such individuals, investment of some part of their superannuation savings in biotechnology research and commercialisation is thus appropriate.

[41] The Society's Internet site can be found at www.medstv.unimelb.edu.au/ASMR

Unfortunately, the current superannuation savings environment is very short term in nature, with returns measured and analysed on a monthly basis, rather than on a timescale commensurate with members' retirement liabilities. County Investment Management hopes that contributions such as this paper will help stimulate debate and financial product innovation to overcome this obstacle and allow members to invest in the GPT that will so greatly affect their retirement. In so doing, we also expect to play our part in ensuring that Australia benefits from the biotechnology revolution.

Acknowledgments

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APPENDIX A: Resolving the US Productivity Paradox

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CHAPTER III: RESOLVING THE US PRODUCTIVITY PARADOX
–Innovation versus Investment in Global Competition–

1. Introduction and Overview

Figures 1 and 2 contrast savings rates and productivity growth rates in both manufacturing and services across the three largest G-7 economies: the US, Japan, and Germany. The savings rate figures represent net national savings, which conflate personal, corporate, and government savings (dissavings in the case of fiscal deficits).

The productivity numbers are taken from pioneering studies on manufacturing and service sector productivity undertaken in the early 1990s by McKinsey & Company's Global Institute (1992, 1993) in Washington D.C., and Pilat and Van Ark (1991). Regrettably, the kinds of historical time series data on service sector productivity we would like to have on hand are not available, so we must make do with late 1980s data.

It is important to note that the productivity data generated by McKinsey & Company are stated in Purchasing Power Parity terms. That McKinsey invested the effort to generate not only PPP measures, but properly-benchmarked PPP numbers is extremely important. For as we have argued in past commentaries, the ultimate purpose of productivity growth comparisons across nations is to contrast the level of real output of goods and services per employee-hour worked. If arbitrary currency market distortions are not removed from the measurement of output and hence of productivity, then the results are largely meaningless for the purpose of transnational comparisons.

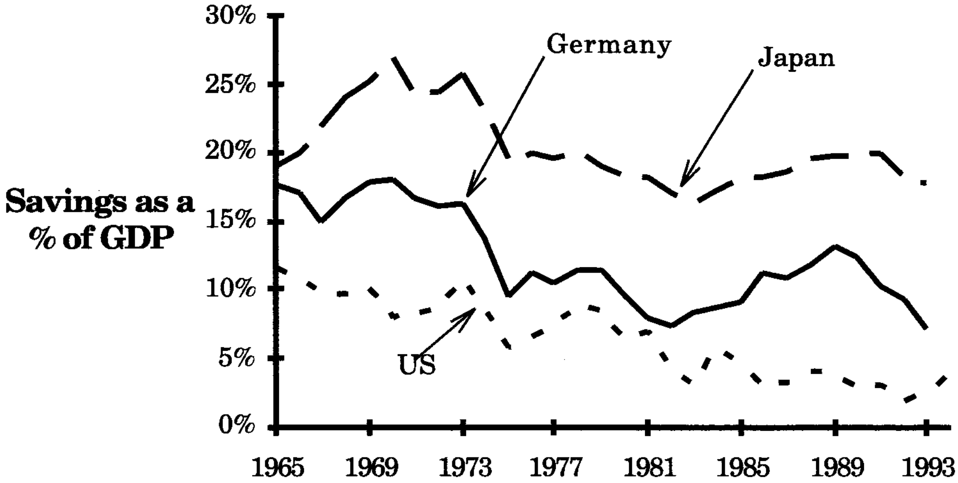
Service Sector Problems: McKinsey made another important contribution. They confronted head-on the vexing problem of defining and measuring output in the case of the service sector. To do this, they proceeded "bottoms-up" by starting at the industry level. Specifically, they measured suitably defined output-per-person-hour levels in five different industries in five different countries.

The results appear in Figure 2, where it should be understood that the US represents the base case of 100 in each industry. In only one case did an industry in another country outperform that in the US: restaurants in France! Several missing entries reveal that the requisite data could not always be obtained. The chosen industries account for 21% of the non-governmental service sector output of the nations in question.

> **TheParadox:** The paradox revealed by the data in the two figures is straightforward: the US maintained a fairly constant productivity lead over Japan and Germany despite having a savings/investment rate which was not only the lowest for three decades, but which *declined* sharply throughout most of the period as well.

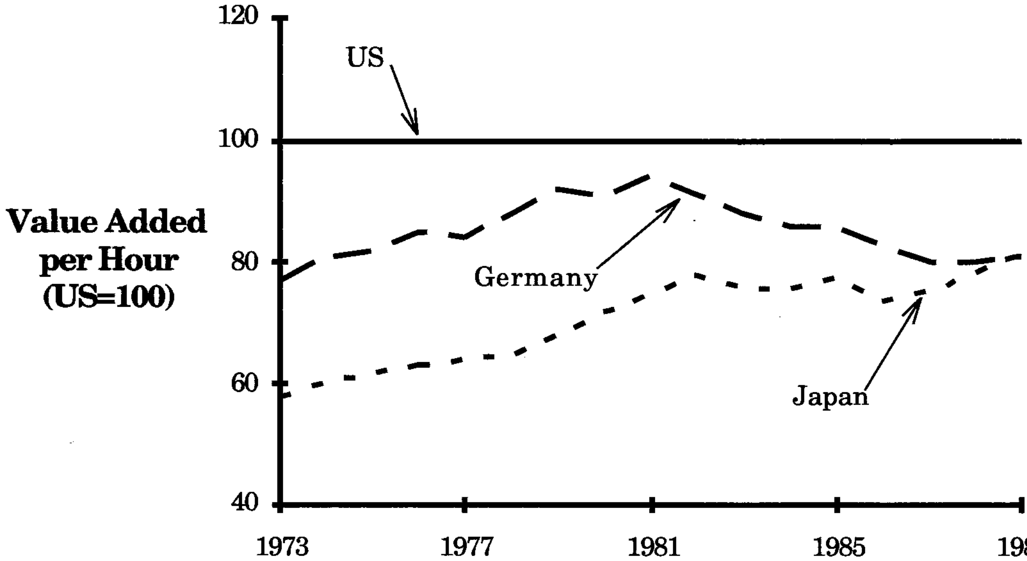
FIGURE 1: THE US PRODUCTIVITY PARADOX

Net Savings Rates



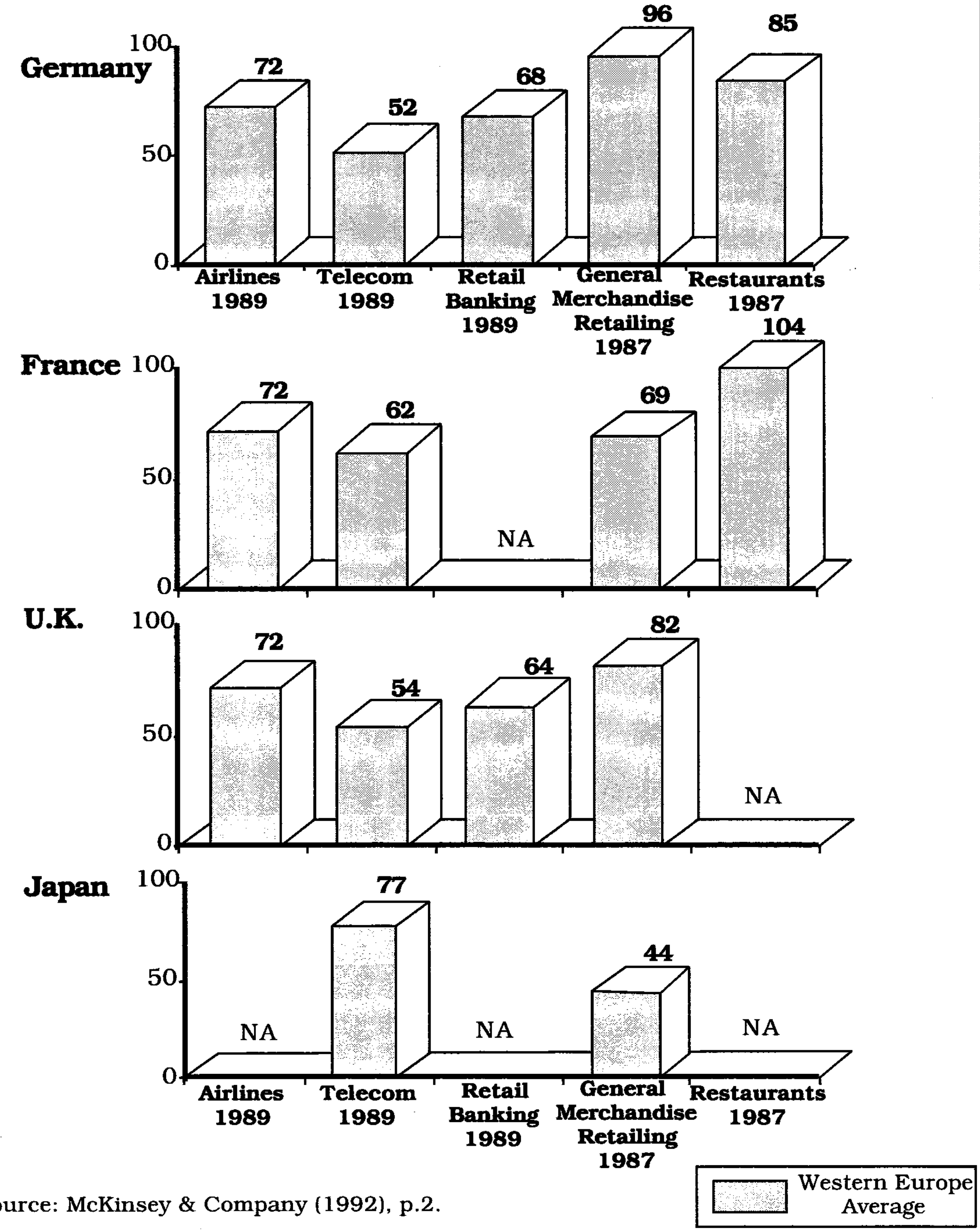
Source: OECD National Accounts

Manufacturing Productivity



Source: Pilat and Van Ark (1991)

FIGURE 2
LABOR PRODUCTIVITY COMPARISON – SERVICE SECTOR
(U.S. Equals 100 in Each Industry)



Source: McKinsey & Company (1992), p.2.

To appreciate the magnitude of this paradox, suppose that back in 1970 a clairvoyant had revealed to investors this particular savings rate data. What would they have inferred from it? Most certainly that the US would end up the *least* productive of the three nations by the mid-1990s, not the most!

The purpose of this essay is to reveal what was wrong in the way we thought then and indeed think now about productivity growth, and thus about economic growth in general.

Overview: In Section 2, we show how the paradox can be resolved at a fairly abstract level. The principal condition is that the technology regime of the economy must exhibit what we shall call multiplicative rather than additive spillover effects. This leads to a discussion in Section 3 of "Multiplicative Innovation Regimes". The concept of "General Purpose Technologies" introduced by Timothy Bresnahan of Stanford University offers real-world examples of how such regimes are propagated. These are discussed in Section 4.

Our sought-after escape from paradox arrives in Section 5. It arises from the commanding lead assumed by the US early in the history of the most important General Purpose Technology of our century: the binary logic of the modern electronic circuit. Next, in Section 6, we assess whether or not the great microprocessor revolution of the past two decades is losing steam. The answer is no, and this is explained in terms of five types of lags which cause such technology cycles to much more long-lived than one might expect.

Finally, we discuss some loose ends in our concluding Section 7. These include Paul Krugman's controversial views that the remarkable growth of the Asian tiger economies is not what it is cracked up to be.

2. Resolution of the Paradox

As Paul Romer pointed out in Chapter III of our May 1995 report, Adam Smith and his followers rarely got things wrong. But one mistake they did make was their identification of high rates of economic growth with high levels of savings/investment. It turns out that both in theory and practice, a high savings rate is neither a necessary nor a sufficient condition for national wealth.

Romer gave us a good example of why this is true. Suppose everyone saves a lot and invests in the one and only capital good produced in the nation, namely the forklift. Then the growth rate of the economy will eventually slow to zero as the marginal productivity of each additional forklift goes to zero. "Factor accumulation" via high savings thus does not guarantee ongoing economic growth.

Role of Innovation: The problem with the classicists and their "Save More!" mantra was their failure to give proper emphasis to the role played by *technological innovation* in stimulating capital and labor productivity growth, and thus economic growth per se. This deficiency in the foundations of macroeconomics would first be redressed by Joseph Schumpeter (1942) – the great economist famous for equating capitalism with "creative destruction" – in the first half of the century. In our forklift example, wealth will come to the nation whose inventors discover a better-and-cheaper replacement for the forklift.

Several decades later, M.I.T. economist Robert Solow (1957) created one of the first and certainly the most celebrated formal models of economic growth in which innovation played an important role. However, innovation was treated as an "exogenous" phenomenon: it emerged randomly from nowhere, outside of human and governmental control. Innovation as an "endogenous" phenomenon was first satisfactorily captured by Romer (1986, 1990) who built upon a pioneering and much earlier paper by Arrow (1962).

It is thus now accepted that *two* conditions are necessary for ongoing economic growth: savings and investment on the one hand, and innovation on the other.

Conditions for Escaping the Paradox: From this elementary observation, it becomes clear how it is *logically possible* to escape the paradox presented above. What first comes to mind is the fact that a low savings nation like the US could maintain its productivity lead by *compensating* on the innovation front. Specifically, it need only maintain a high "innovation quotient" that offsets its low savings rate. (Please see accompanying Figure 3).

> *But this argument will not do the trick. For what must be explained is more difficult, namely that the US maintained a fairly constant productivity differential over time despite a rapidly declining savings rate.*
>
> *The mathematics here are simple, and dictate that the only egress from the paradox lies in a nation's ability to sustain an increasing innovation rate over the decades in question.*

Be sure to note the logical twist that arises here. It does not suffice to cite the official data which show that US productivity growth tripled over the past quarter century, rising from an average all-time low of 0.7% in the 1970s to 1.9% in the 1990s (2.9% if properly measured). For rival countries experienced much the same phenomenon, and as the above data make clear in the case of manufacturing, the productivity differential between the US and its rivals has not changed much.

Thus, to escape the paradox, we must go one level deeper. Since productivity growth is a function of both savings and innovation, and since the savings rate of the US declined precipitously relative to that of other nations, then its innovation rate proper must have risen dramatically.[1]

But what exactly does this mean? And how can we establish that the US exhibited an accelerating innovation quotient? Since there is virtually no pre-packaged data available summarizing the "evidence", we must *deduce* what happened to innovation according to the aggregate data on productivity and savings from a theory of the nature of innovation. In doing so, we shall introduce two interrelated concepts. The first is that of a Multiplicative Innovation Regime. The second is that of a General Purpose Technology. The second is a special case of the first.

Note: Henceforth, some shorthand. When referring to a nation's savings rate, we shall write **SR**. When speaking of its innovation quotient, we shall write **IQ**, a Multiplicative Innovation Regime will be written as **MIR**, and a General Purpose Technology as **GPT**. Doing so will speed things up a bit.

---

1 Some might argue that the decline in the US savings rate is overstated in the above data since they fail to capture the inflow of foreign investment mirroring the US current account deficits which arose in the mid-1980s. But adjusting for such inflows does not materially change the above argument.

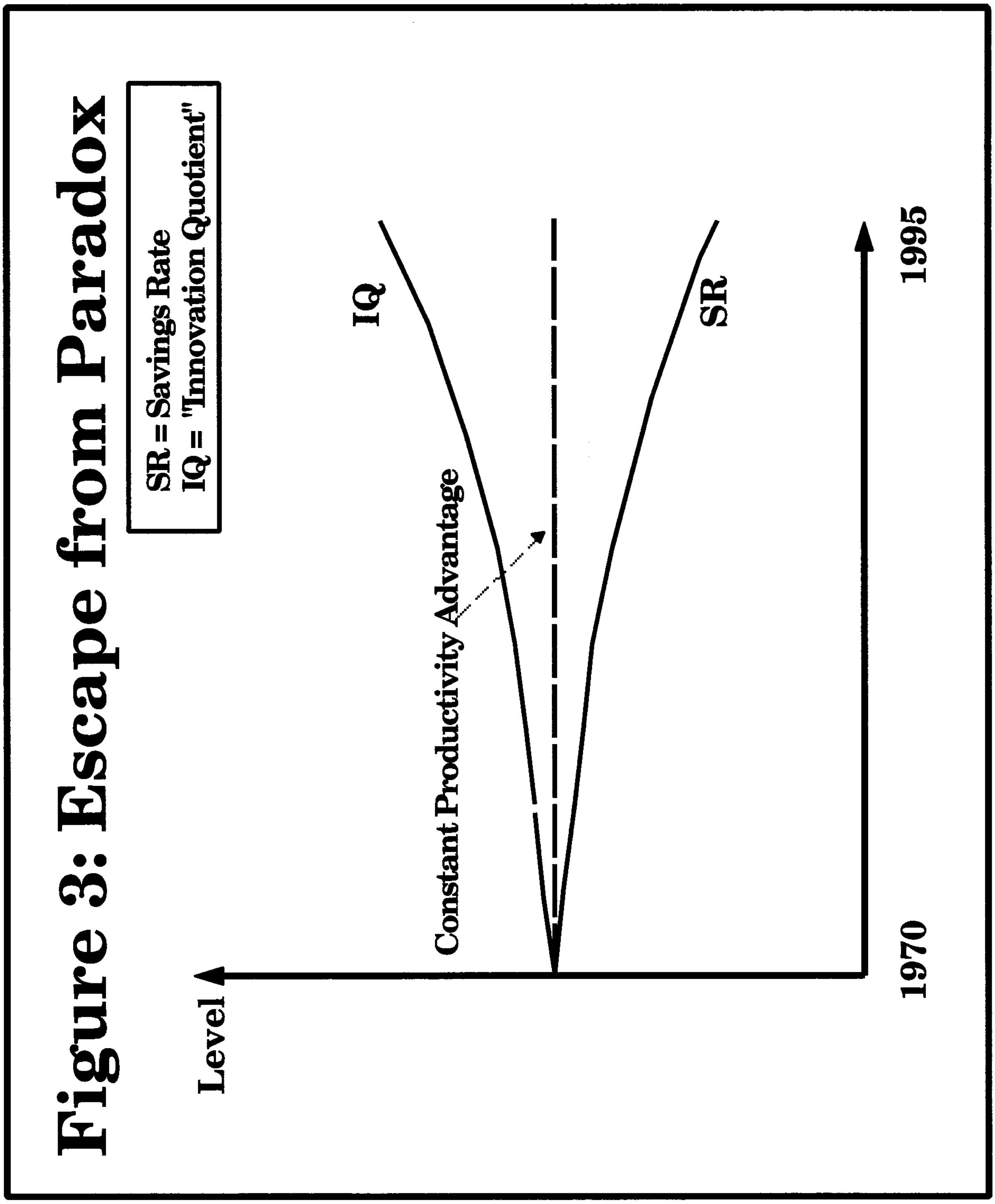
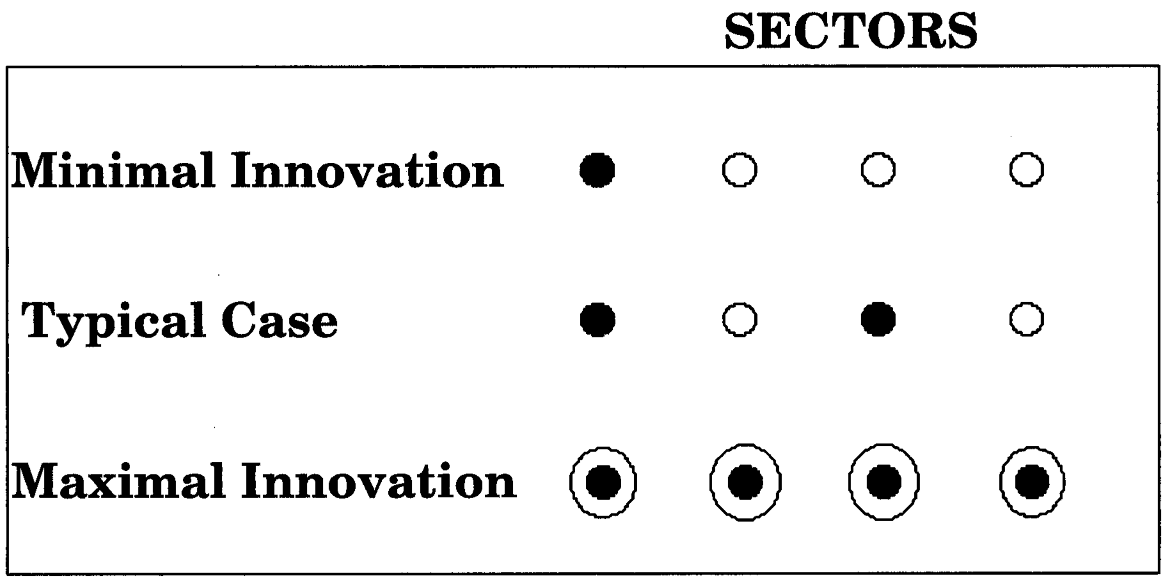


Figure 3: Escape from Paradox
SR = Savings Rate
IQ = "Innovation Quotient"
Level
IQ
SR
Constant Productivity Advantage
1970
1995

Figure 4:
Multiplicative Innovation Regimes



● Denotes an innovation which is sector–specific

◉ Denotes an innovation with maximal spillover effects

3. Multiplicative Innovation Regimes (MIRs)

To make sense of the concept of an accelerating **IQ**, we must clarify the precise relationship between the individual innovations that arise within industries (sectors of an economy) on the one hand and aggregate productivity growth of the economy on the other hand. [1]

To make this linkage clear, we need to utilize the concept of a MIR. Since this is quite abstract, let's start off with an example. Consider the invention of the Gutenberg press in the 15th Century. This revolutionized the life of scribes in monasteries, and raised productivity fantastically. But automated printing did little or nothing for the blacksmith and the farmer, at least for the first hundred years or so.

> *It can be shown that, when all technological innovations are "separable" in this sense, the aggregate productivity growth of an economy is an* <u>*arithmetic*</u> *function of the individual innovations begetting it.*

Conversely, consider the invention of the steam engine, or the electric motor, or the microprocessor. In each case, the initial innovation was seen to boost productivity growth in a host of downstream industries impacted by the original innovation. These secondary innovations would in turn feed back upon the original invention, and boost its productivity in turn.

> *When all innovations possess this spillover property, aggregate productivity growth becomes a* <u>*multiplicative*</u> *function of the individual innovations.*

A technology regime with this latter property is clearly going to be much more productivity-enhancing than one without it, and this is precisely what a MIR is. We have of course stated two polar extremes above. Most real-world cases lie between these polar extremes, with the level of productivity growth dependent upon the degree of spillover effects ("innovational complementarities") between sectors. This concept is illustrated in Figure 4, and explained in more depth in footnote 2 below [2].

---

[1] Paul Romer and others rightly extol the virtues of "exponential growth", in particular how economic growth is an exponential function of the rate of growth of productivity. And indeed it is – the laws of compounding guarantee this. But what is not usually addressed is the precise way in which the (productivity growth) rate at which economic growth compounds is *itself* a function of the structure of innovation-induced productivity gains across different industries. It is this complex linkage we are focusing on here.

[2] To understand this in more detail, contrast the aggregate growth rate in two economies identical in all respects except the degree of "separability" between the innovations of different sectors. [Complete separability implies *no* spillover effects from an innovation in one sector to other sectors.] Our aim is to create two polar cases. Let Economy **A** have **N** equal size sectors, each of which is completely "separable". Let Economy **B** have the same **N** sectors, but this time each exhibits *maximal* innovational spillovers across sectors. That is, an innovation in any one sector of Economy **B** raises productivity by every bit as much as it does on its own sector. *How then do the growth rates of the two economies compare?* The answer is that if each economy experiences

4. General Purpose Technologies (GPTs)

In a fascinating paper, Timothy Bresnahan of Stanford and Manuel Trajtenberg of Tel-Aviv University (1992) discuss the nature and implications of what they call "General Purpose Technologies". Loosely speaking, these are the core technologies which drive downstream areas of technological innovation and economic growth over fairly long time spans ranging from 25 – 50 years. For our purposes, familiarity with GPTs is important because these technologies when they arise *cause* innovation regimes to become *multiplicative* in nature. By understanding them, we can thus better understand the conditions required for MIRs to exist and indeed flourish.

These GPTs have three properties which play an important role in shaping the nature and magnitude of productivity growth over time. The analysis of this point by Bresnahan and Trajtenberg is well worth citing:

> We think of the technologies prevalent in any given period as structured in a hierarchical pattern (i.e., as forming a sort of "technological tree"), which in the simplest case would consist just of two levels: a handful of "basic" technologies at the top (perhaps just one), and a large number of product classes or sectors that make use of the former at the bottom.
>
> Those at the top are characterized first of all by their *general purposeness,* that is, by their performing some generic function that is vital to the functioning of a large segment of existing or potential products and production systems. Such a generic function would be, for example, "continuous rotary motion," performed at first by the steam engine and later on by electrical motors. "Binary logic" would be the corresponding generic function for electronics, the obvious GPT candidate of our times.
>
> The second distinctive characteristic of GPTs is their *technological dynamism*: continuous innovational efforts, as well as learning, increase over time the efficiency with which the generic function is performed. This may show up as reductions in the price/performance ratio of the products, systems or components in which the GPT is embodied, or as multidimensional qualitative improvements in them. As a consequence, the costs of the downstream sectors that use the GPTs as inputs are lowered, they may be able to develop better products, and moreover, further sectors will find it profitable to adopt the improved GPT, thus expanding the range of applications.
>
> Third and last, GPTs are characterized by the existence of *innovational complementarities* (spillover effects) with the application sectors, in the sense that technical advances in the GPT make it more profitable for its users to innovate, *and vice versa.*

---

the same total number of innovations, then the growth rate in economy **B** will be **N** times as great as that in Economy **A**. To state this somewhat differently, innovation *per se* is effectively **N** times more important to growth in Economy **B** than in **A**.

The precise route of escape from our paradox is now at hand. We shall demonstrate how the US assumed a commanding lead several decades ago in what is arguably the most important GPT of the century. In doing so, the US was able (via the algebraic logic of an MIR) to compensate for its declining **SR** with an increasing **IQ**. As a result, it could maintain the productivity differential it has enjoyed over its principal competitors for many decades.

5. The US and "Binary Logic": A Case Study of a GPT

There is little disagreement in the growth literature that the US has traditionally evinced a high level of technological innovation during the entire twentieth century.[1] This is evidenced by **(1)** the predominance of its research universities; **(2)** its number of Nobel laureates; **(3)** the number of its patents in leading-edge technologies; **(4)** its productivity dominance in manufacturing and services as evidenced in the McKinsey data; **(5)** its widely respected tradition of entrepreneurship; **(6)** its absence of those product and labor market rigidities that now burden continental Europe; **(7)** its unique venture capital industry, and **(8)** its increasing dominance in many leading-edge industries of the next century. These include telecommunications, consumer electronics, computer software, computer hardware, video-and-entertainment, and biotechnology.

Electronic Circuits – Today's GPT: It is this last strength **(8)** we wish to focus on. How can the US simultaneously be the leader in virtually *all* of these industries (consumer electronics rejoined this list in 1994)?

The reason is that the US took a commanding lead early in the game in what is arguably the single most important GPT of all time: the logic of binary numbers (formally, Boolean lattices) physically embodied in the (digital) electronic circuit.

This technology gave rise to and interconnected more downstream innovations, faster, than any other GPT in recorded history. But why is this so? What exactly is it that makes (binary) electronic circuits the great driver of progress that they have become? By taking the microprocessor for granted, we lose sight of this all-important issue.

Happily, Bresnahan and Trajtenberg address precisely this question at one point in their paper, and they answer it better than anyone else we know of. The reader is advised to read twice the following rather challenging passage:

> What accounts then for the 'general purposeness' of electronic circuits? The workings of virtually any system and, in particular, of any electro-mechanical system, can be thought of as (and actually be broken down into) a series of steps that transform a given input into a desired outcome. Thus, a traditional watch transforms the power of the spring into an analog signal, depicting time; a washing machine transforms electrically-induced continuous mechanical

[1] The criticism launched in the early 1980s that the US had lost its ability to *commercialize* its innovations was true, at least until the 1990s. But this view is irrelevant to our point here.

traction into a series of actions involving movement of parts, the opening and closing of valves, etc.

Despite their variety, a vast majority of these intervening steps can in principle be done (or be replicated) by the application of binary logic, that is, by activating a circuit consisting of a series of binary elements (e.g., gates, flip-flops, etc.). This is a striking *technological* fact that has reaching *economic* implications. What it says is that the enormous variety of seemingly disparate products, materials, methods of production, etc. conceal the *uniformity* of a few underlying technological principles; these principles, in turn, give rise to potent economic forces that would shape the (endogenous) process of technical change.

Contrary to popular perceptions, substituting binary logic for mechanical parts is in many cases extremely *inefficient*, if measured by the number of steps required by the former, and hence by the number of circuit components and operations involved.

However, as the price and size of circuit components decrease dramatically, and as their reliability improves, it becomes eventually cost–effective to use *them* rather than the old electro-mechanical parts. And, in turn, these dramatic advances in costs, size and reliability are due to a large extent to the tremendous increases in the volume of production of *standardized* circuits, where 'learning' plays a key role.

The authors then demonstrate that the electronic circuit is the dominant technology of our time, and that it exhibits very clearly the key features of a GPT reviewed above. *First,* it has proven to have the inherent potential for persistent and manifold technical advances along its main performances dimensions. *Second,* these advances impinge upon a wide range of applications which, when coupled with complementary innovations by the user sectors, have brought about a reshaping of the universe of goods and services at our disposal.

Resulting Prediction for the US: When these aspects of the digital revolution are factored into our earlier arguments about the nature of MIRs and their implications for aggregate productivity growth, the following theoretical prediction emerges:

As the leader exploiting these new technologies, the US should have been experiencing an increasing rate of growth in its IQ during the 1970 – 1995 period.

Note that this was the period when the electronic circuit GPT was domesticated via the ever-more-powerful "chip", with the result that new applications and downstream innovations proliferated profusely. A significant sector of the US economy became a MIR.

Happily, this prediction seems to fit the empirical facts. It also explains away the paradox with which we began in Section 1.

6. The Future – Is the Revolution Over?

Is the revolution launched by the GPT of binary logic nearing its completion? No. Moreover, the greatest risk to investors is that they will think "Yes", and jump ship. But why will the revolution continue? The answer is subtle, and can best be understood by citing four obstacles which explain why it took so long for productivity gains from the digital revolution to show up in the official numbers in the first place. [Keep in mind here that the digital computer has been around since the late 1940s.] The nature of these lags also clarifies why GPT-based technology waves are particularly long waves – a phenomenon with which most investors are both uncomfortable and unfamiliar.

1. Lags in the InnovationProcessItself: The great economic virtue of the chip is that it raises the benefits and/or lowers the costs of innovation in so many related fields. But precisely because this is true, the *total* impact of the microprocessor on productivity and growth will not be realized until its spillover effects (complementarities) are recognized and in turn acted upon by other entrepreneurs throughout the economy.

2. Lags in Business Applications: Suppose that entrepreneurs do comprehend the possibilities inherent in a GPT, and attempt to create the downstream innovations stipulated by (1) above. Suppose, moreover, that these innovations become economically viable once the microprocessor arrives on the scene. For example, some farsighted entrepreneur perceives that the "fax machine" will become a commercial success, because businesses will eventually deem the technology to be "indispensable". He creates the blueprint and prototype. What next? Who has benefited?

The truth is that there will be no increase in *aggregate* productivity until the fax machine is *widely* used years later. But in order this will only happen once people take it for granted. But for these downstream users to take the new technology for granted, a host of related innovations must first be in place: offices with complementary equipment (e.g. computer programs which manage faxes), speedy and reliable links to transmit messages throughout the economy, etc. It takes a lot of time for these related goods and services to accumulate to the extent required before the fax machine is fully accepted and makes its ultimate contribution to productivity growth.

3. Lags due toPsychology: Resistance to change is pandemic. "We don't really need a xerox machine or a personal computer". [Recall that IBM turned down opportunities to buy both Xerox and DOS for a pittance in earlier days]. The Internet was deemed a hacker's toy for over a decade. Virtual reality was for video arcades, not Boeing. Desktop publishing was a luxury we thought we could never afford. And so on.

4. Lags due to Standardization Problems: The full advantages of new technologies stemming from a GPT such as the electronic circuit cannot be reaped until complex sets of uniform standards are in place. Even today, brand name PCs don't communicate with one another. Recall Betamax versus VHS? Digital TV? Putting Lotus Notes up on the Net?

7. Conclusion

In concluding, there are a number of issues we would have liked to address, but could not. For example, Paul Krugman of Stanford University (1994) has re-examined the nature of the success of the Asian Tiger economies from an interesting standpoint. As we have done, he distinguishes the relative contribution to Asian growth due to "factor stuffing" (high SR and capital accumulation) on the one hand, and IQ on the other. He concludes that the tigers' success has largely been "bought" by high levels of savings and investment that are forced, and that will decline. Such growth is expensive (in terms of foregone current consumption), whereas IQ-based growth is cheaper, and thus preferable.

Because of such arguments, Krugman does not believe that the Asian economies will perform in the future as well as they have in the past. Factor stuffing strategies run into laws of diminishing returns, whether of the kind experienced in the USSR, or in Asia. However, we believe that he overstates his case because a good part of the capital accumulation in these Asian economies *does* embody new innovations. These economies are not simply accumulating more and more of the same capital goods (i.e., more "forklifts") as Krugman seems to imply. But this and related issues will have to be postponed to some future date.

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