290 Pages × 250 words per page = 72 500 words.

Endogenous Innovation and Economic Growth

Stephen James Redding,
Nuffield College,
Oxford.

28 May, 1996

Thesis Submitted to the University of Oxford in Fulfilment of the Requirements for the D. Phil in Economics, Trinity Term 1996

I certify that this thesis is my own original work, except where otherwise stated, and that it is within the upper limit on length.

Abstract

Endogenous Innovation and Economic Growth

Stephen James Redding, Nuffield College, Oxford

Thesis Submitted to the University of Oxford in Fulfilment of the Requirements for the D. Phil. in Economics, Trinity Term 1996

This thesis seeks to explain variations in growth rates across countries and time within an endogenous growth framework. Intentional investments by profit-seeking agents determine the rate of technological progress, which in turn determines an economy's rate of growth.

Chapter 2 surveys the existing literature and introduces the quality ladder model of endogenous growth, upon which much of this thesis builds. Chapter 3 argues that entrepreneurs' incentives to invest in Research and Development (R & D) depend upon workers' complementary investments in human capital. Strategic complementarities between the two investments, together with indivisibilities in the R & D technology, may result in an economy becoming trapped in a "low skills" equilibrium.

Chapter 4 argues that the realisation of the full productive potential of an innovation may be dependent upon a lengthy process of further improvement. The existing literature is surveyed and a distinction between fundamental and secondary innovation drawn. Chapter 5 argues that this distinction provides a rationale for a "penalty" to being a pioneer, and an alternative explanation for income convergence to those suggested in the existing literature. Depending on the magnitude of secondary knowledge spillovers in production and research, a pioneer may be characterised by a higher or lower level of research employment and rate of economic growth than an otherwise identical latestarter. Technological lock-in may occur.

Chapter 6 investigates the relationship between technological change and international trade. We argue that an economy may face a trade-off between specialising according to its current pattern of comparative advantage and specialising in sectors where the potential for rapid productivity growth may generate such an advantage in the future. A distinction between static and dynamic comparative advantage is drawn. Chapter 7 relates the evolution of the cross-section distribution of income over time to patterns of international trade, and considers the relevance of the concept of "international competitiveness" for an economy's standard of living.

Acknowledgements

It is no exaggeration to say that this thesis would not have been possible without Philippe Aghion and Steve Nickell. I will never be able to thank each of these remarkable people enough for all that they have taught me. They have been a constant source of advice, encouragement, thought provoking discussions and insightful comments. I really cannot say how grateful I am to them, and this thesis could not have been written without their help.

A number of other individuals have kindly provided comments and suggestions on the material that forms this thesis. I am especially grateful to Jon Temple and Gavin Cameron for their thoughtful comments and suggestions. I am also extremely grateful to Anthony Atkinson, Christopher Bliss, Richard Blundell, Andrea Boltho, Cecilía Garcia-Peñalosa, Chol-Won Li, Dan Maldoom, Meg Meyer, James Mirrlees and John Muellbauer. I would also like to thank the participants of seminars at an Innovation Workshop (Centre for Economic Performance), Nuffield College, University College London, Royal Economic Society Conference (1995), Royal Economic Society Conference (1996) and European Economic Association Conference (1995).

I would like to thank Nuffield College for all the facilities that it has provided me with and the ESRC for financial support. I also acknowledge the financial support of the Bank of England. The views expressed in this thesis are those of the author, and should not be attributed to any other individual or institution. Any errors are also the author's responsibility. This thesis is dedicated to my father, without whom I would never have got this far.

Preface

I have tried to keep notation as consistent as possible throughout the thesis. In each Chapter, notation is defined when introduced. In addition, notation is summarised Chapter by Chapter in an Annex at the end of the thesis.

Contents

Chapter 1

Introduction

> "We are not used to thinking of ideas as economic goods, but they are surely the most significant ones that we produce ... We once used iron oxide as a pigment in cave paintings. An elaborate set of ideas now lets us use it to store magnetic signals on audio cassettes, video cassettes and computer disk drives."[1]

Between 1870 and 1992 real output per capita in the United Kingdom rose by a factor of almost 5, while that in the United States increased more than 8 times over.[2] These figures correspond to average annual growth rates in real output per capita of 1.30 per cent and 1.80 per cent respectively in the two economies. Such apparently small differences in growth rates meant that the U.S. rose from 15th to 1st in the world distribution of income, while the U.K. fell from 2nd to 15th.[3] Nonetheless, these average figures conceal considerable variation over time. Between 1950 and 1973, the U.K. and U.S. enjoyed growth rates in real output per capita of 2.47 per cent and 2.42 per cent respectively; while, between 1870 and 1913 the corresponding figures were 1.01 per cent and 1.82 per cent respectively.

---

[1] Paul Romer (1993), *150 Economist Years*, pp. 86.

[2] All figures in this first paragraph are derived from Maddison (1995) and Crafts (1996).

[3] In 1870, real output per capita in Australia was \$3801, compared to \$3263 in the U.K. (1990 U.S. dollars).

Thus, rates of economic growth vary considerably both across countries and over time, and these differences have substantial implications for living standards. This thesis is concerned with theoretical models of endogenous growth, which seek to explain these variations in terms of differences in economic parameters and the economic decisions made subject to these parameters. The first central tenet of this thesis is that *long-run rates of economic growth are related in an important way to the rate of technological progress.*

This hypothesis receives support from a number of sources. Firstly, from formal growth accounting exercises such as those of Solow (1957) and Maddison (1996). Although Solow's early estimates have been subsequently revised downwards, a substantial proportion of output growth remains unexplained by increases in capital and labour inputs. The most plausible explanation for this Total Factor Productivity (TFP) growth is technological progress, and this explanation receives considerable econometric support.[4] Secondly, a wide range of informal evidence supports the role of technological progress in generating output growth. It is difficult to conceive how modern manufacturing would proceed without electricity, the internal combustion engine or the computer. Many of the products that we now take for granted such as television, the video cassette recorder and the microwave are but recent innovations.

The second central tenet of this thesis is that *the rate of technological progress is endogenously determined.* Considerable evidence exists concerning the importance of serendipitous learning in generating productivity improvement. Nonetheless, following Schmookler (1966)

---

[4] See for example the discussion in Chapter 3.

and Schumpeter (1942), we argue that the rate of technological progress depends to a large degree upon the intentional choices of profit-seeking agents,

> "the historical record of important inventions in petroleum refining, paper making, railroading, and farming revealed ... the stimulus was the recognition of a costly problem to be solved or a potentially profitable opportunity to be seized; in short, a technical problem or opportunity evaluated in economic terms."[5]
>
> "... even the inventing itself, as will be more fully explained in a moment, was a function of the capitalist process ... It is quite wrong ... to say, as so many economists do, that capitalist enterprise was one, and technological progress a second, distinct factor in the observed development of output; they were essentially one and the same thing or, as we may also put it, the former was the propelling force of the latter."[6]

Firms seek to accumulate knowledge by investing in Research and Development (R & D). These expenditures exhibit considerable variation across countries, industries and time. The magnitude of this variation is illustrated by the fact that, in 1921, only 2275 scientists and engineers were employed in research activities in the United States. Yet, by 1985, the figure had reached 600 000.[7] Even within the OECD over the period 1975 to 1985, the average annual share of gross domestic expenditure on R & D in GDP ranged from 0.20 per cent in Greece and Turkey to 2.55 per cent in the United States.[8]

Thus, this thesis will be concerned with models of endogenous growth in which technological progress is both an important determinant of growth and the result of profit-seeking choices by economic agents. In light of the centrality of these ideas to the writings of Joseph Schumpeter,

---

[5] Schmookler (1966), pp. 199.

[6] Schumpeter (1942), pp. 110.

[7] Source: Mowery and Rosenberg (1989).

[8] Source: Nonneman and Vanhoudt (1996), Appendix 1.

any endogenous growth model satisfying these criteria will be termed *Schumpeterian.* The concept of technological progress that will be used is a very broad one, and an innovation is defined as follows.

Definition 1 *An innovation describes any change in the organisation of production that results in either a reduction in production costs (or equivalently an increase in Total Factor Productivity (TFP)), an improvement in product quality or the introduction of new products (an increase in product variety).*

Throughout much of this thesis, we will be concerned with the case where innovations result in increases in the quality of existing products or the productivity of existing processes. From the definition above, it is clear that *technological* knowledge is embodied in the production process, and in principle may differ from the stock of *scientific* knowledge used in research. In the one-dimensional models of technological progress in the next two Chapters, this distinction will not emerge and the stock of technological knowledge will be identical to that of scientific knowledge. The distinction will be given some content in the richer models of technological progress considered in later chapters. Nonetheless, the point remains that, in principle, one may distinguish between *inventions* (additions to the stock of scientific knowledge) and *innovations* (changes in the process of production or additions to the stock of technological knowledge).

The main body of the thesis begins in Chapter 2, where we survey the existing literature on Schumpeterian models of endogenous growth. The analysis begins with the neoclassical model of growth, and then considers early attempts to endogenise the rate of technological progress as an externality of the production process. This is followed by the exposition of the two main classes of Schumpeterian models: the Romer (1990) model of increasing variety and the Aghion and Howitt (1992) model of rising product quality. While a variety-based approach successfully models the non-rival and partially excludable nature of technology as an economic good, it fails to capture the fact that growth is essentially a process of *creative destruction.* This idea is central to the "quality ladder" approach of Aghion and Howitt that will be the starting point for the analysis of much of the rest of this thesis. We then proceed to consider some extensions to and qualifications of the basic quality ladder approach. Particular attention is paid to role of knowledge spillovers in research in generating endogenous growth.

Chapter 3 is concerned with the idea that an agent's incentives to engage in Research and Development (R & D) may well depend upon her expectations of the extent of complementary investments. Of such complementary investments, workers' choices of education and general skills are perhaps the most important, and the analysis extends the basic quality ladder model to incorporate an endogenous supply of skilled labour. Strategic complementarities between human capital and R & D, when combined with indivisibilities in the R & D technology, provide a rationale for the idea that an economy may become trapped in a "low-skill / low quality" equilibrium.

In Chapter 4 we introduce the idea that the full productive potential of an innovation may not be realised until after a gradual process of further development. Technological progress becomes essentially multi-dimensional, and Chapter 4 surveys existing Schumpeterian models with this feature. Considerable evidence exists that learning by doing is an important source of productivity improvement subsequent to the original introduction of an innovation. The Chapter begins with the model of Young (1991), in which learning by doing in any one good is bounded, but in which spillovers of learning by doing across goods gradually lead to adoption of more sophisticated technologies over time.

Young (1993a) extends the analysis to allow the discovery of technological blueprints for new varieties of goods to be the result of endogenous investments in Research and Development (R & D). In one equilibrium, new varieties of goods are not produced until some time after their discovery, and a distinction does indeed emerge between the stocks of scientific and technological knowledge. The analysis then proceeds to consider the Schumpeterian model of Aghion and Howitt (1996a) in which a more general distinction is drawn between *fundamental* and *secondary* innovations. Fundamental innovations constitute "major breakthroughs," such as the steam engine, which open whole new paths for further innovation. Secondary innovations correspond to the "incremental improvements," such as the separate condenser and the boring mill in the steam engine's case, which realise the opportunities latent in each fundamental innovation.

Chapter 5 applies the distinction between fundamental and secondary innovation to consider whether or not there is in some sense a "penalty" to being the first economy to innovate. The idea that there might be such a "penalty" to being a pioneer has received considerable informal attention in the economic history literature. We consider four forms that the penalty to being a pioneer might take: a reduced incentive to invest in the discovery of the next technology, technological lock-in, a slower rate of economic growth and a lower level of economic welfare. If pioneer status is indeed associated with a lower rate of growth of GDP per capita, it provides an alternative explanation for *income convergence* to those suggested in the existing literature. Chapter 5 examines which factors induce either an advantage to an early start or a penalty to being a pioneer within a general equilibrium model of endogenous growth. We are able to address the question of whether a drastic event, such as a war, may both accelerate growth and increase welfare in a pioneering economy.

In Chapter 6, we return to a somewhat simpler, uni-dimensional model of innovation to consider the relationship between international trade, technological progress and economic growth. A distinction is drawn between the traditional or *static* notion of comparative advantage and a second concept of *dynamic comparative advantage* that emerges in models of endogenous growth and trade. While a number of authors have referred to dynamic comparative advantage, the concept is yet to be explicitly defined and its importance remains un-noted. In general, an economy's pattern of dynamic comparative advantage depends upon the nature of international specialisation and the potential to reallocate resources over time (*intertemporal* advantage).

The analysis suggests that an economy may face a trade-off. On the one hand, it may specialise in those sectors in which it currently has a *static* comparative advantage. On the other hand, it may choose to enter sectors in which it may attain such an advantage in the future as a result of the pattern of *dynamic* comparative advantage. This trade-off may be particularly marked in the transition economies of Central and Eastern Europe, where current and potential future patterns of comparative advantage may diverge significantly.

Chapter 7 applies the dynamic Ricardian model developed in Chapter 6 to two further issues. Firstly, we consider necessary and sufficient conditions for income per capita in a backward economy to converge towards and overtake the level in an initially more advanced counterpart. The analysis of the penalty to being a pioneer in Chapter 5 is undertaken in the context of a closed economy, where we consider the comparative static effect of an increase in the interval of time since the development of one technology (a move from latestarter to pioneer) holding other things constant. Chapter 7 may be seen as extending the analysis to the open economy.

Secondly, it is possible to evaluate the role of "international competitiveness" in determining an economy's standard of living. On the one hand, a number of authors have recently claimed that the slow growth of U.S. living standards since the 1970s is due to a lack of "international competitiveness." On the other hand, Paul Krugman has argued vehemently that the improvement in an economy's standard of living depends almost entirely upon its domestic rate of productivity growth and that the concept "international competitiveness" is irrelevant. Chapter 7 addresses these issues in the context of the dynamic Ricardian model of Chapter 6 and relates the competitiveness debate to the concept of *dynamic comparative advantage.*

Chapter 2

Technological Innovation and Economic Growth

2.1 Introduction

This Chapter surveys the existing literature on Schumpeterian models of endogenous growth. The starting point for the analysis is the neoclassical model of growth of Solow (1956) and Swan (1956), which is introduced in Section 2. Diminishing returns to physical capital mean that capital accumulation alone is unable to sustain growth in per capita income. In order to generate continuing per capita income growth, one is forced to introduce an exogenous rate of technological progress.

A number of early attempts were made to endogenise the rate of technological progress. However, each of these attempts was beset by the problem of how technological progress was to be rewarded in a world of perfect competition where there were already constant returns to scale to labour and physical capital. Early endogenous growth models either assumed that technological progress was an unintended and unrewarded by-product of the production process (see for example Romer (1986)) or assumed that there were constant returns to scale to the accumulation of a "broad" concept of capital, including for example both human and physical capital (see for example Lucas (1988) and Rebelo (1991)).

Section 3 introduces the first class of Schumpeterian models, beginning with Romer (1990), in which technological progress is assumed to take the form of an increase in the variety of differentiated intermediate inputs. Endogenous investments in profit-seeking Research and Development (R & D) determine the rate of introduction of new product varieties and the economy's long-run rate of growth. Although the economy's growth rate is endogenous, the analysis abstracts from the obsolescence of existing ideas and techniques typically induced by an innovation.

Section 4 introduces the idea that, as argued by Schumpeter (1942), growth is essentially a process of *creative destruction.* This idea is formalised in the second class of Schumpeterian models, beginning with Aghion and Howitt (1992), in which technological progress is assumed to take the form of an increase in the *quality* of existing products or the productivity of existing processes. This is the subject of Section 5, which introduces the so-called "quality ladder" model of growth of Aghion and Howitt (1992). Each innovation renders obsolete an existing technology and destroys the flow of monopoly profits enjoyed by an incumbent producer.

Section 6 considers a variety of extensions to and qualifications of the basic quality ladder model. In particular, we will be concerned with the nature of knowledge spillovers in the research sector and empirical evidence surrounding the scale effects implied by many endogenous growth models. Finally, Section 7 concludes.

2.2 Exogenous versus Endogenous Growth

In this Section, we consider the implications of the Solow-Swan (1956) model of economic growth, and early attempts to endogenise the rate of technological progress.

2.2.1 The Solow-Swan Model

Consider a one-sector economy characterised by the following aggregate production function,

$$Y_\tau = G(A_\tau, K_\tau, L_\tau) = A_\tau.F(K_\tau, L_\tau), \qquad (2.1)$$

where time is continuous and indexed by τ, A is a productivity parameter representing the state of technological knowledge, K denotes physical capital and L denotes unskilled labour. $F(\cdot,\cdot)$ is assumed to be a strictly concave function of capital and labour individually, and to be homogeneous of degree one in the two factors of production. Furthermore, we assume that $F(\cdot,\cdot)$ satisfies the so-called Inada conditions.[1]

An example of a production function satisfying both sets of properties is the Cobb-Douglas

---

[1] That is, the marginal product of capital (or labour) approaches infinity as capital (or labour) goes to zero and approaches zero as capital (or labour) goes to infinity,

$$\lim_{K\to 0} F_K = \lim_{L\to 0} F_L = \infty, \qquad \lim_{K\to\infty} F_K = \lim_{L\to\infty} F_L = 0,$$

function $Y_\tau = A_\tau.F(K_\tau, L_\tau) = A_\tau.K_\tau^\alpha.L_\tau^{1-\alpha}$ (where $0 < \alpha < 1$). Since $F(\cdot,\cdot)$ is homogeneous of degree one, it may be written in the intensive form,

$$y_\tau = A_\tau.F(k_\tau, 1) = A_\tau.k_\tau^\alpha, \qquad 0 < \alpha < 1, \tag{2.2}$$

where lower case letters denote per capita variables. In Solow (1956), aggregate saving is assumed to equal a constant proportion s $(0 < s < 1)$ of aggregate output.[2] Hence, in the absence of depreciation, $\dot{k}_\tau = s.A_\tau.k_\tau^\alpha$. Taking logs in (2.2), differentiating with respect to time and using the expression for $\dot{k}_\tau$ above, we obtain,

$$\frac{\dot{y}_\tau}{y_\tau} = \frac{\dot{A}_\tau}{A_\tau} + \alpha s.A_\tau.k_\tau^{\alpha-1}, \tag{2.3}$$

In the absence of exogenous technological progress ($A_\tau = A$ for all τ), per capita income growth will cease. Capital accumulation alone is unable to sustain long-run economic growth, since diminishing marginal returns mean that each additional unit of physical capital contributes less and less to final goods output. In (2.3), the economy's growth rate is monotonically decreasing in k_τ (since $0 < \alpha < 1$) and tends asymptotically to zero.

---

[2] Ramsey (1928), Cass (1965) and Koopmans (1965) consider neoclassical models of growth where savings are endogenously determined by intertemporal consumer optimisation.

2.2.2 Technological Change

In order to explain continuing per capita income growth, one is forced to assume the existence of exogenous technological progress ($\dot{A}/A = g > 0$). This has the somewhat unpalatable implication that the determinant of the economy's long-run rate of growth is unexplained and lies outside the model. This implication was made all the more unattractive by Solow's (1957) empirical results that 87.5 per cent of the increase in U.S. gross output per man between 1909 and 1949 was unexplained by increases in physical capital and labour inputs and was instead due to Total Factor Productivity (TFP) growth.

In principle, Total Factor Productivity (TFP) growth may have a number of different causes. However, technological progress is perhaps the most plausible cause, and a wide range of evidence suggests for example that investments in R & D are significant determinant of TFP growth.[3] As a result, a number of attempts were made to endogenise the rate of technological progress in the neoclassical model, including for example Arrow (1962) and Shell (1966). However, each of these attempts faced the horns of a dilemma.

On the one hand, if technological progress is to be endogenised, then the decisions that make A grow must be rewarded. On the other hand, if final good production is assumed to exhibit constant returns to scale in K and L, it must exhibit increasing returns to scale in the three factors A, K and L. In this case, each factor can no longer be paid its marginal

---

[3] See for example Griliches (1980) and Patel and Soete (1988).

product (since by Euler's Theorem this would more than exhaust the value of output). Thus, the assumption that technological progress is rewarded is inconsistent with the joint hypothesis of constant returns to scale (in K and L) and perfect competition.

Romer (1986), in the first model of truly endogenous growth, sought to avoid the horns of this dilemma by following Arrow (1962) in assuming that technological progress is the result of *learning by doing.*[4] As such, it is an unintentional effect or externality of production and may proceed unrewarded. Learning by doing is assumed to result from physical investment. Each firm j is characterised by a Cobb-Douglas production function $Y_j = A.K_j^{\alpha}.L_j^{1-\alpha}$ and takes the economy-wide stock of knowledge A as given. However, as result of economy-wide learning by doing, the productivity parameter A depends upon cumulative investment, $A = \left(\sum_j K_j\right)^{\eta}$. Endogenous growth results in the case where $\alpha + \eta = 1$ and, in contrast to the Solow-Swan model, there are constant returns to physical capital accumulation.

Thus, early theories of endogenous growth assumed either that technological progress was a pure externality of production activity (as in Romer (1986)) and/or that there were constant returns to the accumulation of physical and/or human capital (see for example Rebelo (1991) and Lucas (1988)).[5],[6] Either of these approaches has its limitations. On the one hand, any

---

[4] In Arrow (1962), the economy's growth rate remains exogenous. See the discussion in Chapter 4.

[5] The assumption of constant returns to physical capital or to some broader concept of capital led to this approach being termed the "AK-model" of growth.

[6] Jones and Manuelli (1990) show that, even if there are diminishing returns to physical capital accumulation for a range of values of K, endogenous growth may still result if the marginal and average product of capital are bounded from below. Implicitly, endogenous growth requires that the Inada condition $\lim_{K\to\infty} F_K = 0$ be violated. A simple example of this is where the production function takes the form,

$$Y = G(A, K, L) = A.K + B.K^{\alpha}.L^{1-\alpha},$$

model in which growth is purely the result of physical and human capital accumulation is difficult to reconcile with evidence of significant Total Factor Productivity (TFP) growth. On the other hand, an externality-based explanation of technological change ignores the wide range of case study and econometric evidence suggesting the importance of purposive investments in Research and Development (R & D) in determining Total Factor Productivity (TFP) growth.

The Schumpeterian approach argues that intentional investments by profit-seeking agents are the prime determinant of the rate of technological progress and an economy's rate of growth. In the next Section, we introduce the first Schumpeterian model of endogenous growth: the Romer (1990) model of growth through increasing product variety.

2.3 Variety and Growth

An externality-based model of technological change is not only inconsistent with case study and econometric evidence. More fundamentally, it implicitly assumes that ideas are *public goods* (non-rival and non-excludable). As such, it fails to recognise the defining features of knowledge as an economic good. On the one hand, ideas are certainly *non-rival*: once an invention has been made the same idea may be used again and again at no extra cost.[7] On the other hand, ideas are typically *partially excludable*: an inventor of a new product may prevent others from producing exact copies of her product (through for example the patent system). However,

---

[7] For example, the knowledge that carbon based products such as wood and coal burn may be used by any suitably informed individual, and has already been used in a wide variety of different contexts.

excludability is only partial, since for example an inventor typically cannot prevent others from using the ideas embodied in her product in research.[8]

The first model to incorporate these features of technological knowledge into a macroeconomic model of growth is that of Romer (1990). Although the production function exhibits increasing returns to scale in A, K and L,[9] technological progress may be rewarded because of the introduction of *imperfect competition.* Partial excludability enables inventors to appropriate quasi-rents from their discoveries, and it is these quasi-rents that provide the very incentive for research.

In Romer (1990), technological progress takes the form of the introduction of new varieties of intermediate inputs. Each of these intermediate inputs may be thought of as durable, specialised capital good (e.g. lathes or computers), while an increase in the variety of intermediate inputs over time may be interpreted as an increase in specialisation. The economy is composed of three sectors: final output, intermediate inputs and research.[10] Final goods output Y is produced with human capital H, unskilled labour L and intermediate inputs $x(j)$ according to the following Cobb-Douglas technology,[11]

---

[8] For example, Apple Macintosh could not prevent Microsoft exploiting the idea of a mouse-based operating system.

[9] In a way, increasing returns is implicit in the very fact that knowledge is non-rival. Since it is not necessary to replicate non-rival inputs, the standard replication argument to justify constant returns to scale cannot be made. Furthermore, invention is typically characterised by fixed costs.

[10] Romer (1987) presents a model in which the introduction of new varieties of intermediate inputs (or increasing specialisation) is a source of endogenous growth. However, there is no research sector: the technological blueprints for new varieties of intermediate inputs are assumed to be freely available to entrepreneurs.

[11] In order to simplify notation, we suppress an implicit dependence upon time, except where important.

$$Y = H_Y^{\alpha}.L^{\beta}.\int_0^A x(j)^{1-\alpha-\beta}dj, \qquad 0<\alpha,\beta<1, \quad 0<\alpha+\beta<1, \tag{2.4}$$

where A_τ denotes the mass of varieties of intermediate inputs that have been discovered by time τ and may be thought of as indexing the state of technological knowledge.

Intermediate inputs are produced from final goods output, and we assume that $\eta > 0$ units of output are required to create one unit of any durable input. Romer (1990) defines general capital K as a measure of the output forgone to produce all existing varieties of intermediate inputs, and hence $K = \eta.\int_0^A x(j)dj$. Following Ramsey (1928), a representative consumer is assumed to allocate output between current and future consumption c to maximise the discounted sum of current and future utilities,

$$\max_{c_t} U_\tau = \int_\tau^\infty e^{-\rho(t-\tau)}.u(c_t)dt, \tag{2.5}$$

subject to an intertemporal budget constraint, the appropriate transversality condition and the requirement $c_t \geq 0$ for all t. Under the assumption that instantaneous utility takes the constant intertemporal elasticity of substitution form, $u(c_\tau) = \frac{c_\tau^{1-\sigma}-1}{1-\sigma}$, we obtain the familiar Ramsey condition,

$$\frac{\dot{c}_\tau}{c_\tau} = \frac{r_\tau - \rho}{\sigma}, \tag{2.6}$$

where ρ denotes the subjective rate of time preference and $1/\sigma$ the intertemporal elasticity of substitution. Since (2.6) holds for each representative consumer, it also holds in the aggregate and defines an upward sloping relationship between the rate of growth of aggregate consumption C and the interest rate r_T.

New varieties of intermediate inputs are produced by skilled labour in the research sector. Each skilled researcher is assumed to have access to the entire existing stock of technological knowledge, and we assume,

$$\dot{A} = \lambda.H_A.A, \tag{2.7}$$

Each inventor is assumed to receive an infinitely-lived patent for her idea, which she may then either employ in intermediate input production or sell to the intermediate goods sector. Intermediate inputs are horizontally differentiated, and the owner of the patent for each variety of intermediate input is a monopolist facing a downward sloping demand curve.[12] In equilibrium, the value of a patent is given by the discounted flow of monopoly profits from intermediate input production. Hence, the incentive to engage in R & D is a decreasing function of the interest rate at which future profits are discounted. This yields a downward sloping relationship between the rate of growth of designs for new intermediate inputs and the interest rate r_T.

In steady-state equilibrium, consumption C, output Y, general capital K and the stock

---

[12] In equilibrium, no two individuals will choose to purchase the patent for the same variety of intermediate inputs.

of technological knowledge A all grow at a constant exponential rate $\xi = \lambda.H_A$. A unique steady-state equilibrium exists characterised by a constant allocation of skilled labour between production and research,

$$\xi = \frac{\lambda H - \Lambda\rho}{\sigma\Lambda + 1}, \qquad \Lambda \equiv \frac{\alpha}{(1-\alpha-\beta).(\alpha+\beta)}, \tag{2.8}$$

The economy's growth rate is increasing in the supply of skilled labour H, the productivity of research λ and the intertemporal elasticity of substitution $1/\sigma$, and decreasing in the subjective rate of time discount ρ.

2.4 Creative Destruction

In Romer (1990), the laissez-faire growth rate (2.8) is always less than is socially optimal. This reflects the existence of two positive externalities. Firstly, inventors do not internalise the increase in the productivity of existing intermediate inputs that results from the discovery of each new variety and the associated increase in specialisation.[13] Secondly, each inventor does not take into account the fact that, by increasing the stock of designs for intermediate inputs, she thereby raises the productivity of future research. The technology for producing new designs of intermediate inputs (2.7) is linear in the existing stock of designs, and each

---

[13] In equilibrium, each intermediate input is produced in a constant amount $\bar{x}$. Hence, from (2.4),

$$Y = H_Y^{\alpha}.L^{\beta}.A.\bar{x}^{1-\alpha-\beta},$$

generation of researchers "stands upon the shoulders"[14] of existing discoveries (we term this the *intertemporal spillover*).

The first of these externalities reflects the fact that intermediate inputs are horizontally differentiated. Final goods production exhibits a demand for variety and productivity is increasing in the number of varieties of intermediate inputs produced. Since technologies are horizontally differentiated, in equilibrium, all varieties of intermediate inputs are demanded in positive amounts.

In reality, technologies are not only horizontally but also *vertically* differentiated. Technological progress not only takes the form of the introduction of new products, but also of increases in the quality of existing products or the productivity of existing manufacturing processes. Vertical differentiation means that new technologies typically render *obsolete* their older predecessors. Thus, the speed or quality of personal computers has increased dramatically with the successive discovery of the 286, 386, 486 and Pentium chips, each of which has rendered its predecessors obsolete. As argued by Schumpeter (1942), growth is essentially a process of *creative destruction*,

> "... The fundamental impulse that sets and keeps the capitalist engine in motion comes from the new consumers' goods, the new methods of production or transportation, the new markets, the new forms of industrial organisation that capitalist enterprises creates ... [examples] ... [these examples] illustrate the same process of industrial mutation that incessantly revolutionises the economic structure *from within*, incessantly destroying the old one, incessantly creating a new one. This

---

[14] "If I have seen further (than you and Descartes) it is by standing upon the shoulders of Giants." Newton (1675), cited in Caballero and Jaffe (1993).

process of Creative Destruction is the essential fact about capitalism."[15]

In order to capture this obsolescence and the destructive aspect of the growth process, we turn in the next Section to the "quality ladder" model of Aghion and Howitt (1992). Intentional investments in Research and Development (R & D) by profit-seeking agents endogenously determine the rate of quality improvement and long-run growth. Furthermore, the obsolescence of existing technologies means that the laissez-faire growth rate need not always be less than is socially optimal.

2.5 Quality and Growth

Aghion and Howitt (1992) consider an economy composed of three sectors: final output, intermediate inputs and research. Time is continuous and is indexed by $\tau \geq 0$. Final goods output Y is produced with the output x of a single intermediate goods sector.[16] For simplicity, we assume that the production technology is Cobb-Douglas,[17]

$$Y_\tau = A_\tau . x_\tau^\alpha, \qquad 0 < \alpha < 1, \tag{2.9}$$

where A denotes the quality or productivity of intermediate inputs and rises over time as innovations occur.[18] Each innovation is assumed to raise the quality of intermediate inputs by

---

[15] Schumpeter (1942).

[16] As will be discussed below, the analysis is easily extended to the case of more than one sector.

[17] Aghion and Howitt (1992) consider more general production technologies.

[18] In the present framework, quality and productivity are essentially equivalent.

the constant proportion $\gamma > 1$. As shown in Figure 1, technologies may be viewed as steps on a "quality ladder," each step γ times the height of the previous step. Hence, the quality of intermediate inputs may be indexed by $m = 0, 1, ..., M$, where m denotes the interval starting with the m^{th} innovation (or with time zero in the case of $m = 0$) and ending just before the $m + 1^{\text{st}}$ (where M denotes the current state of the art quality of intermediate inputs).[19]

Final goods output is chosen for the numeraire and hence $p_\tau^Y = 1$ for all τ. Intermediate inputs are assumed to be produced with skilled labour (the sole primary factor of production) according to a constant returns to scale technology $x = H^x$. The economy consists of a continuum of representative consumers of constant mass H. Each consumer is endowed with one unit of skilled labour, which is supplied inelastically with zero disutility. Preferences are assumed to be intertemporally additive separable, with linear instantaneous utility defined over consumption of the final good c. Consumers are thus *risk neutral* and the interest rate r_τ equals the subjective rate of time preference ρ for all τ.

As in Romer (1990), technological progress is the result of intentional investments in Research and Development (R & D). However, in this case, following Segerstrom et al. (1990), research is assumed to be an essentially *uncertain* process. A researcher j who employs a flow of skilled labour $H_m^r(j)$ in research during interval m is assumed to innovate (and develop technology $m + 1$) with probability $\lambda . H_m^r(j)$, where $\lambda > 0$.[20] The research technology is the same

---

[19] In equilibrium, all variables are constant over the interval of time between any two innovations. Hence, variables may be indexed by the state of technology m.

[20] Aghion and Howitt (1992) consider more general research technologies.

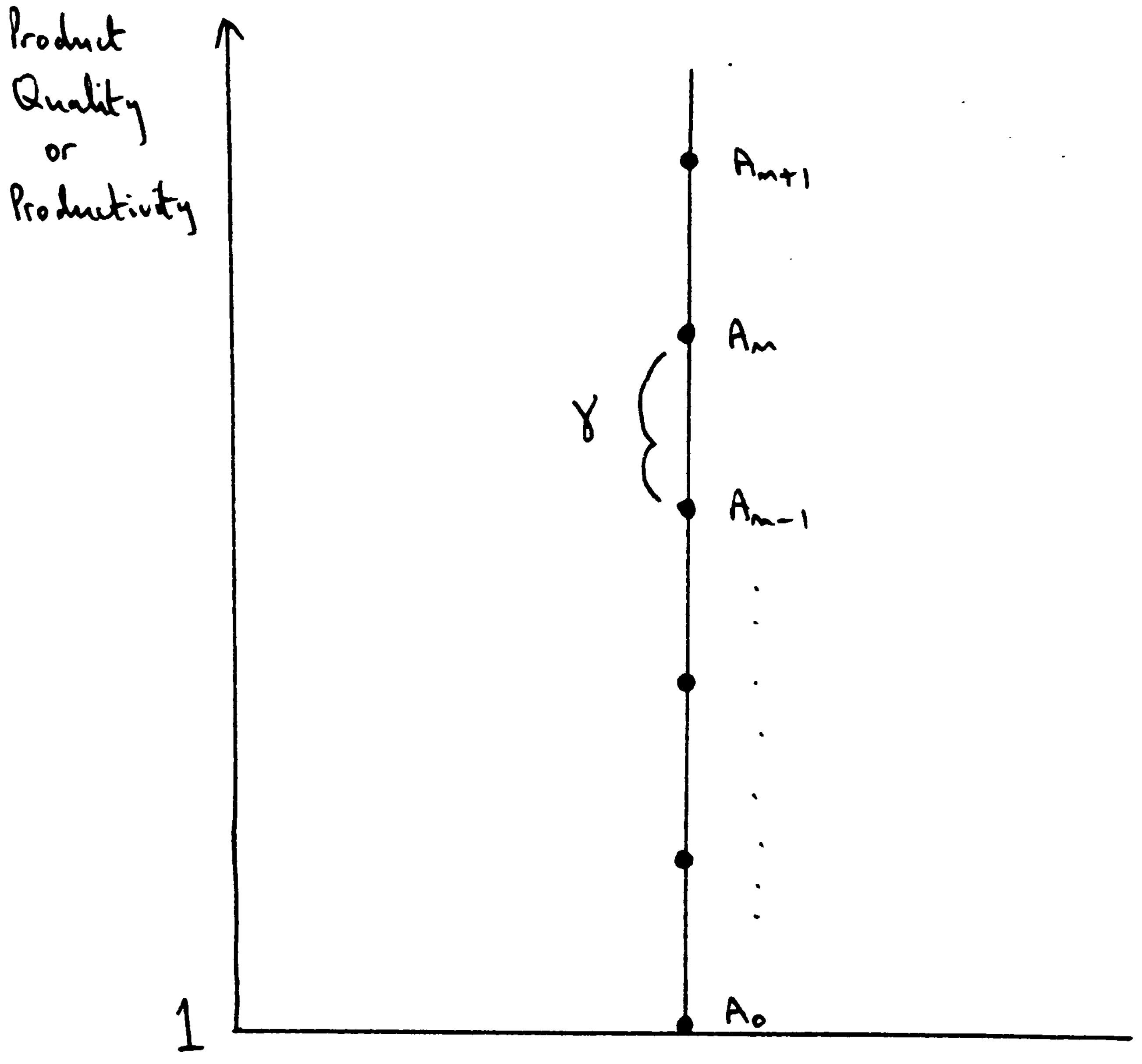


Figure 1: Each innovation may be viewed as a step on a "quality ladder."

for all individuals. Hence the instantaneous Poisson probability that an innovation occurs is,

$$\iota_m = \lambda.H^r_m, \tag{2.10}$$

The probability of innovating is assumed to be independent of the existing stock of technological knowledge. Successful researchers gain an infinitely lived patent for their innovation, which they may either choose to implement themselves or sell to the intermediate input sector at a price V_{m+1} equal to the expected value of the $m+1^{\text{st}}$ innovation.

The owner of the m^{th} patent is a monopolist of the state of the art intermediate goods technology, and faces an inverse demand curve derived from (2.9), $p^x_m(x) = \alpha.A_m.x^{\alpha-1}_m$. Throughout the following, we assume that innovations are *drastic*. That is, a monopolist does not face competition from the preceding quality of intermediate inputs at the profit-maximising monopoly price.[21] Since intermediate inputs are vertically differentiated, in equilibrium, only the state of the art quality is employed by final goods producers. As a result, each innovation renders obsolete an existing technology and destroys the flow of profits received by an incumbent monopolist (*value obsolescence*).

The intermediate goods monopolist chooses output x to maximise the instantaneous flow of profits $\pi_m = p^x_m(x).x - w_m H^x$, given the inverse demand curve for intermediate inputs and the skilled wage w_m,

---

[21] The condition for innovations to be drastic is $\gamma > \alpha^{-\alpha}$ and may be derived from the Cobb-Douglas cost function for final goods output. The analysis is easily extended to the *non-drastic* case (Aghion and Howitt (1992), Section 5).

$$\begin{aligned} x_m &= \arg\max_x \{\alpha A_m x^\alpha - w_m x\} \\ &= \left(\frac{w_m/A_m}{\alpha^2}\right)^{1/\alpha-1} \end{aligned}, \tag{2.11}$$

Hence, from the inverse demand curve above, $p^x_m(x) = w_m/\alpha$. While,

$$\begin{aligned} \pi_m &= \{\alpha A_m x^\alpha - w_m x\} \\ &= \left(\frac{1-\alpha}{\alpha}\right).w_m.x_m \end{aligned} \tag{2.12}$$

We define a ***productivity adjusted wage*** $\omega \equiv w_m/A_m$. From (2.11) and (2.12), both the equilibrium flow of intermediate inputs x_m and the equilibrium flow of profits π_m are *decreasing* functions of the productivity adjusted wage.

2.5.1 Equilibrium Research Employment

Each research firm j chooses employment $H^r_m(j)$ to maximise the expected flow of profits from research. Agents are assumed to have *perfect foresight.* Hence, each research firm solves $\max_{H^r_m(j)} \lambda H^r_m(j).V_{m+1} - w_m H^r_m(j)$, where V_{m+1} denotes the expected value of the $m+1^{\text{st}}$ innovation. From the first-order condition to this problem, we obtain,

$$w_m \geq \lambda.V_{m+1}, \qquad H^r_m(j) \geq 0, \qquad \text{with at least one equality,}$$

The research technology is common to all individuals and exhibits constant returns to scale. Hence, the above must also hold in the aggregate and constitutes a *free entry* condition for research,

$$w_m \geq \lambda.V_{m+1}, \qquad H^r_m \geq 0, \qquad \text{with at least one equality,} \tag{2.13}$$

In equilibrium, all research is undertaken by outside firms.[22] V_{m+1} is determined by the asset equation,[23]

$$\rho.V_{m+1} = \pi_{m+1} - \lambda.H^r_{m+1}.V_{m+1},$$

Hence,

$$V_{m+1} = \frac{\pi_{m+1}}{\rho + \lambda.H^r_{m+1}}, \tag{2.14}$$

General equilibrium is fully characterised by the free-entry condition (2.13) and the requirement that the labour market clear,

$$H^x_m + H^r_m = H, \tag{2.15}$$

Combining the free entry condition (2.13), the expression for V_{m+1} (2.14), the expression for equilibrium profits (2.12) and labour market clearing (2.15), we obtain,

---

[22] The value to an incumbent monopolist of making the next innovation is $V_{m+1} - V_m$, which is strictly less than V_{m+1}. This is an example of the so-called *replacement effect*: by innovating a monopolist forgoes a stream of current profits (see for example Tirole (1988), Chapter 10). The counteracting *efficiency effect* is not present here: since technologies are vertically differentiated, a successful innovator does not face competition at the profit-maximising monopoly price.

[23] See Appendix for derivation.

$$\underbrace{\omega_m}_{MC(H^r_m)} \geq \underbrace{\frac{\lambda\gamma\left(\frac{1-\alpha}{\alpha}\right)\omega_{m+1}(H - H^r_{m+1})}{\rho + \lambda H^r_{m+1}}}_{MB(H^r_{m+1})}, \quad H^r_{m+1} \geq 0, \quad \text{with at least one equality,} \tag{2.16}$$

where we use the fact $A_{m+1} = \gamma.A_m$ and $x = H^x$. The left hand side of (2.16) denotes the marginal cost of research, $MC(H^r_m)$, and the right hand side the marginal benefit, $MB(H^r_{m+1})$. An increase in current research employment H^r_m reduces the flow of skilled labour in intermediate input production and thereby raises the marginal cost of research (the productivity adjusted wage). In contrast, the marginal benefit of research depends upon research employment H^r_{m+1} in the interval $m + 1$ over which a successful innovator will enjoy a flow of monopoly profits. Higher future research employment both raises the productivity adjusted wage (reducing the instantaneous flow of monopoly profits) and increases the probability a successful researcher will be replaced by subsequent innovation. Each of these effects reduces the value of an innovation and the marginal benefit of research.

Since the marginal cost of research $MC(H^r_m)$ is strictly *increasing* in current research employment and the marginal benefit $MB(H^r_{m+1})$ strictly *decreasing* in future research employment, it follows that research employment this period is a decreasing function of research employment next period,

$$H^r_m = \psi(H^r_{m+1}), \tag{2.17}$$

where $\psi : [0, H) \rightarrow \Re_+$ is a strictly decreasing function wherever it is positive valued.

Equilibrium is illustrated in Figure 2, where we plot the marginal cost and benefit of research. Throughout the following, we restrict consideration to stationary equilibria, characterised by a constant level of research employment $H^r_m = H^r_{m+1} = \hat{H}^r$ that solves $H^r = \psi(H^r)$. The marginal cost of research is strictly increasing and the marginal benefit strictly decreasing in research employment. Hence, under the assumption $\lambda\gamma\left(\frac{1-\alpha}{\alpha}\right)H/r > 1$, a stationary equilibrium characterised by a positive level of research employment must exist.[24]

From (2.11) and (2.16), $H^r_m = H^r_{m+1}$ requires $\omega_m = \omega_{m+1}$. Hence, from (2.16), the stationary equilibrium level of research employment $\hat{H}^r$ solves,

$$1 = \frac{\lambda\gamma\left(\frac{1-\alpha}{\alpha}\right)(H - \hat{H}^r)}{\rho + \lambda\hat{H}^r}, \tag{2.18}$$

As in Romer (1990), equilibrium research employment is increasing in the productivity of research λ and the supply of skilled labour H, and decreasing the subjective rate of time discount ρ. Equilibrium research employment is also increasing in the size of innovations γ and decreasing in the elasticity of final output with respect to intermediate inputs α.

---

[24] Because research employment this period is a decreasing function of research employment next period, non-stationary equilibria also exist. One such equilibrium is the two-cycle (H^r_0, H^r_1) illustrated in Figure 2. The expectation of a high level of research in odd intervals leads to a low intensity of research in even periods and vice-versa.

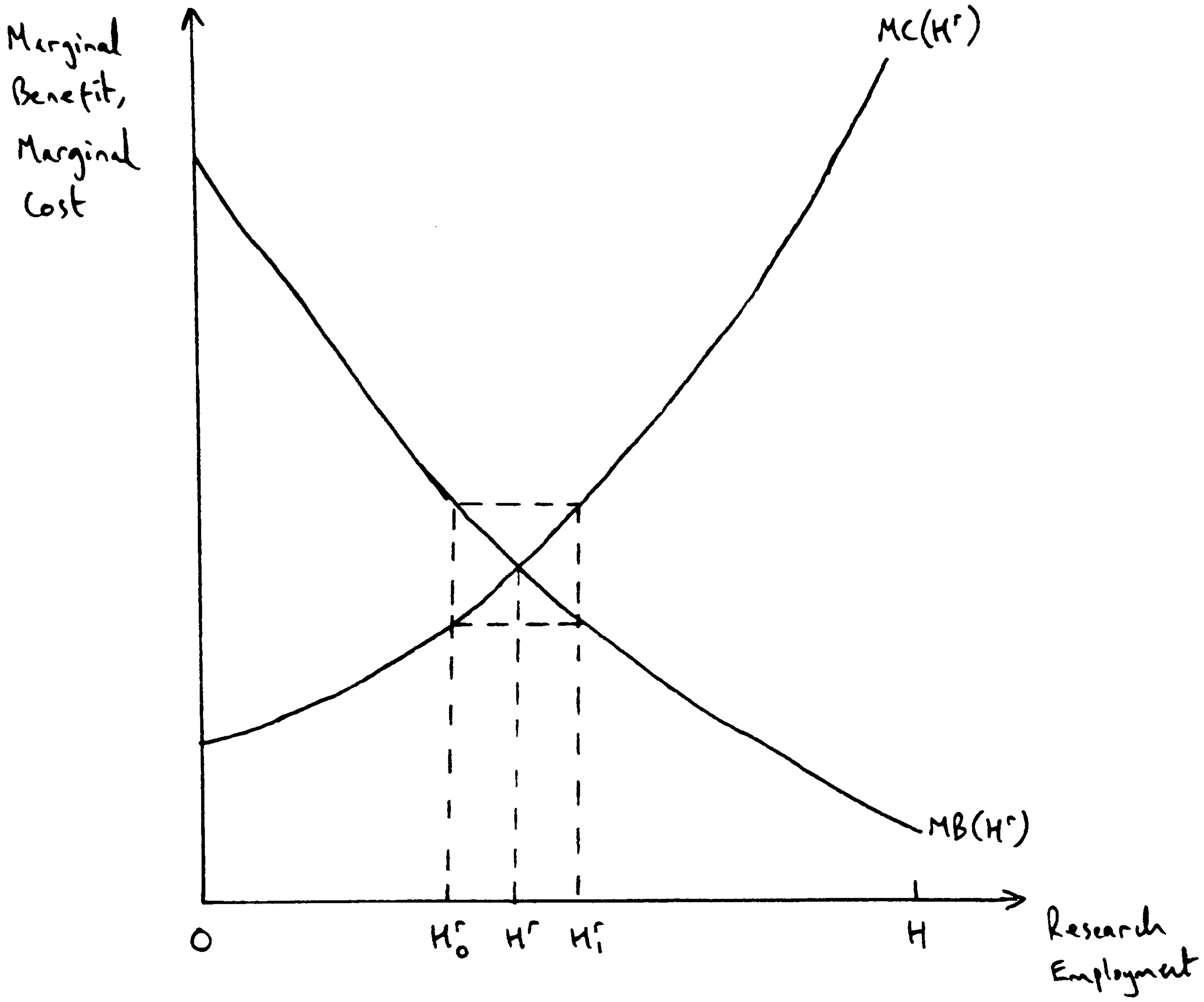


Figure 2: The effect of future research on current research.

2.5.2 The Equilibrium Growth Rate

Equilibrium employment in research determines the instantaneous probability that an innovation occurs $\iota = \lambda.H^r$. The interval between two innovations is exponentially distributed with mean $1/\lambda H^r$, and hence the economy's rate of growth over any arbitrary interval of time is stochastic. Nonetheless, it is possible to evaluate the economy's expected or average rate of growth ζ over a unit interval of time $(\tau, \tau+1)$,

$$\zeta = \lambda.\hat{H}^r.\ln\gamma, \tag{2.19}$$

The economy's average rate of growth is endogenously determined by the expected rate of quality improvement. As such, the average growth rate is monotonically increasing in research employment $\hat{H}^r$ and the size and probability of innovations γ and λ.

2.5.3 Welfare

The *value obsolescence* induced by each innovation means that, in contrast to Romer (1990), the laissez-faire growth rate may be either higher or lower than is socially optimal. Aghion and Howitt (1992) show that the socially optimal level of research employment in the Cobb-Douglas case is,

$$1 = \frac{\lambda(\gamma-1)\frac{1}{\alpha}(N - H^{r*})}{r - \lambda H^{r*}(\gamma-1)}, \tag{2.20}$$

From equation (2.18), there are three differences between the socially optimal and laissez-faire growth rates. Firstly, the *social discount rate* in the denominator of the marginal benefit term is given by $r - \lambda H^{r*}(\gamma - 1)$ as compared with the private discount rate $r + \lambda \hat{H}^r$. A social planner takes into account the fact that the benefit to the next innovation will continue forever, whereas the private research firm attaches no weight to the benefits that accrue beyond the succeeding innovation. Secondly, $(\gamma - 1)$ replaces γ in the numerator of the marginal benefit term. This is the *business-stealing effect*: a private research firm does not internalise the loss to the previous monopolist caused by an innovation.

Finally, the term $\frac{1}{\alpha}$ replaces the term $\frac{1-\alpha}{\alpha}$ in the numerator of the marginal benefit term. This is actually a combination of two effects. On the one hand, there is the *appropriability effect* whereby a private research is only concerned with the flow of profits to be achieved from an innovation rather than the increased flow of output. On the other hand, there is also a *monopoly distortion effect*, whereby the social cost of research employment exceeds the private cost, because in laissez-faire the alternative use of skilled labour is a monopolist (the incumbent producer of the latest generation of intermediate inputs).

The divergence between the private and social discount rates and the appropriability effect imply that the laissez-faire growth rate is less than socially optimal. However, the business-stealing and monopoly distortion effects imply exactly the converse. Hence, the laissez-faire growth rate may be either higher or lower than is socially optimal.

2.6 Extensions and Qualifications

The quality ladder approach is able to endogenise the rate of technological progress and long-run growth in such as way as to capture the fact that growth is essentially a process of *creative destruction*. In this Section, we consider some extensions to and qualifications of the basic quality ladder model. A wide range of possible extensions exist. In the present Chapter, we restrict attention to the introduction of multi-sectors and of horizontal differentiation to allow old technologies to coexist for some time alongside new.[25] In terms of qualifications, we consider the role of knowledge spillovers in the research sector and the existence of scale effects.

2.6.1 Multi-sectors and Horizontal Differentiation

Grossman and Helpman (1991a Chapter 4, 1991b) extend the analysis to the case where there exists a fixed continuum of intermediate goods sectors. In each sector, the quality of intermediate inputs rises over time as innovations occur. The log of each sector's output enters final goods production additively separably, and in equilibrium final goods producers allocate their expenditure evenly across all sectors. The outputs of different sectors are thus horizontally differentiated, while within sectors technologies are vertically differentiated.

The vertical differentiation of technologies in Aghion and Howitt (1992) (and in each sector in the Grossman and Helpman setup) means that, in equilibrium, only the state of art quality of

---

[25] Aghion and Howitt (1996b, Chapter 3), Grossman and Helpman (1991a, Chapter 5) and Redding (1994) consider the introduction of physical capital. Aghion, Dewatripont and Rey (1995) and Aghion, Harris and Vickers (1995) consider the relationship between competition and economic growth.

intermediate inputs is employed in final goods production. In reality, although new technologies render obsolete their older predecessors, the two sets of technologies may coexist for some time. Young (1993a) cites the example of the steamship and its predecessor the sailing ship: "Although as early as 1850 steamships dominated sailing ships on short routes, it was not until the mid-1880s ... after a variety of design changes and metallurgical advances ... that they universally dominated the older technology."[26]

One explanation for this phenomenon is that new technologies are both vertically and horizontally differentiated from old. Thus, Caballero and Jaffe (1993) assume that instantaneous utility is a CES function of the consumption of a variety of qualities $m \in (-\infty, M_\tau]$ of intermediate inputs,

$$c_\tau = \left[\int_{-\infty}^{M_\tau} \{x_\tau(m).e^m\}^\alpha \, dm \right]^{\frac{1}{\alpha}}, \qquad 0 < \alpha < 1, \tag{2.21}$$

Each innovation is of a higher quality than existing technologies. Nonetheless, it is an imperfect substitute for those technologies,[27] and in equilibrium a range of qualities of intermediate inputs are demanded in positive amounts. The extent of value obsolescence is parameterised by the elasticity of substitution between old and new technologies $\sigma = \frac{1}{1-\alpha}$. Young (1993a) adopts a similar specification.[28]

---

[26] Young (1993a), pp. 446.

[27] For example, although compact disk players are acknowledged to produce sound of a higher quality (less interference or distortion), a number of individuals still prefer the sound produced by a record player (which is often described as richer or less clinical).

[28] As will be discussed in Chapter 4, Young (1993a) also allows the productive potential each innovation to be

2.6.2 Knowledge Spillovers and Scale Effects

In Aghion and Howitt (1992), as in Romer (1990), the research sector is characterised by an *intertemporal spillover.* Each generation of researchers "stands upon the shoulders" of previous discoveries, and uses the existing stock of knowledge to produce new varieties or higher qualities of intermediate inputs. In Romer (1990), the technology for producing new varieties of intermediate inputs is linear in the existing stock of designs A. In Aghion and Howitt (1992), each innovation is assumed to raise the quality of intermediate inputs by a constant proportion $\gamma > 1$ (so that $A_{m+1} - A_m = (\gamma - 1).A_m$), while the probability of innovating is assumed to be independent of the existing stock of technological knowledge.

In some way, the assumption that the probability of innovation is independent of the existing stock of ideas is implausible. Often one discovery will suggest lines of further inquiry and thereby increase the productivity of research directed at making the next discovery. Thus, one of the major innovations in the cotton industry, the mule (1779), was essentially a combination of two earlier innovations, the water-frame (1763) and the jenny (1764).[29] Caballero and Jaffe (1993) extend the "quality ladder" model to allow the productivity of research parameter λ to be endogenously determined by the existing stock of all previous discoveries.

In Caballero and Jaffe (1993), the productivity of research is determined by two forces. Firstly, the *diffusion* of innovations in the research sector is no longer assumed to be instanta-

---

realised gradually through learning by doing.

[29] Source: Aspin (1981). I am grateful to Tim Leunig for this example.

neous. Once has idea has been discovered, it diffuses to other researchers with Poisson probability $\mu \geq 0$. Hence, the probability that an idea discovered at time t has diffused by time τ is simply $(1 - e^{-\mu(\tau - t)})$. Secondly, once an idea has diffused, its "usefulness" or productivity in research is assumed to depend upon the distance between that idea and the current technological frontier. Thus, the productivity of an diffused idea originally discovered at time t in research undertaken at time τ is assumed to equal $\delta.e^{-\beta(M_\tau - M_t)}$ where $\delta > 0$, $\beta \geq 0$. By expanding the technological frontier, each innovation reduces the usefulness of existing ideas or induces *knowledge obsolescence.* In the case where diffusion is instantaneous $(\mu \to \infty)$, $\lambda_\tau = \lambda = \delta/\beta$.

In both Romer (1990) and Aghion and Howitt (1992), the fact that the technology for accumulating ideas is linear in the existing stock of ideas is central in generating steady-state endogenous growth. The existing stock of ideas is assumed to spillover to researchers in such a way that the cost of increasing the stock of ideas by a given *proportion* remains constant. However, it is unclear *a priori* why this intertemporal knowledge spillover should be such that the exponent on the existing stock of ideas in the R & D equation is exactly equal to 1. More generally, as argued by Jones (1995b) one might suppose that,

$$\dot{A}_\tau = \lambda.H_\tau^\tau.A_\tau^\phi, \qquad \phi \geq 0, \tag{2.22}$$

In the special case where $\phi = 1$, endogenous growth occurs. Permanent changes in the productivity of research parameter λ or in any of the determinants of equilibrium research employment will have a permanent effect upon the economy's rate of growth. Hence, an economy's growth rate would be expected to exhibit persistence in the face of exogenous variation in any of these parameters. However, Jones (1995a) finds that growth rates in the OECD exhibit surprisingly little persistence.[30]

The prediction that an economy's growth rate is increasing in the quantity of resources devoted to R & D is essentially a *scale effect*. Other things equal, an economy characterised by a greater stock of the resource used intensively in the research sector should exhibit a higher rate of growth (see equations (2.8) and (2.18)). Jones (1995a) seeks to test this hypothesis directly by relating rates of economic growth to the flow of resources employed in Research and Development (R & D). While in the last 40 years, the number of scientists engaged in R & D in OECD economies has grown dramatically, rates of growth show no such dramatic rise.[31]

Thus, Jones (1995a,b) argues that time series evidence is inconsistent with the scale effects and output persistence implied by the endogenous growth theories of Romer (1990) and Aghion and Howitt (1992) (where $\phi = 1$). Instead, it is argued that the evidence implies $\phi < 1$. In this case, since $\dot{A}/A = \lambda.H^{\tau}.A^{\phi-1}$, the rate of technological progress is monotonically decreasing in the existing stock of technological knowledge A. Profit-seeking Research and Development (R & D) is no longer a determinant of the economy's steady-state rate of growth, and the

---

[30] See also Easterly *et al.* (1993).

[31] For example, between 1950 and 1987, the number of scientists and engineers engaged in R & D in the U.S. increased by a factor of 5 from under 200 000 to nearly 1 million. Per capita growth rates show no such increase. (Source: Jones 1995b).

role of technological progress becomes directly analogous to the role of physical capital in the Solow-Swan (1956) model.

However, a number of points should be made. Even if $\phi < 1$, the productivity of research and the determinants of equilibrium research employment still affect the economy's rate of growth in the transition to steady-state. If ϕ is sufficiently close to 1, then this transition may be extremely slow and the conclusions of endogenous growth theory may be seen as an approximation to the truth.[32] Furthermore, the evidence in Jones (1995a,b) is far from conclusive: there are a number of reasons for questioning both the evidence cited and the conclusions drawn from it. Space precludes a full empirical evaluation of the Schumpeterian framework. Hence, we restrict consideration to the most important points.[33]

Firstly, alternative evidence exists that supports the Schumpeterian approach. Caballero and Jaffe (1993) calibrate a quality ladder model, extended in the manner discussed above, to U.S. patent and patent citation data. Patents are assumed to correspond to ideas, while patent citations are employed as a measure of ideas used in research. The resulting measure of the rate of invention is found to correlate quite highly with low frequency movements in aggregate U.S. consumption and production. In addition, a number of empirical studies find evidence that rates of economic growth are indeed correlated with the structural parameters suggested

---

[32] Indeed, Jones (1995b) provides simulation results that suggest the transition to steady-state may be very slow.

[33] See Aghion and Howitt (1996b, Chapter 9) and Temple (1996) for empirical evaluations of the Schumpeterian approach.

by Schumpeterian models.[34]

Secondly, several other studies have sought to test for the scale effects implied by endogenous growth theory. The evidence is generally mixed. However, Kremer (1993) argues that very long-run historical evidence on the relationship between population growth and technological change (from 1 million B.C. to 1990) is consistent with the existence of scale effects.[35] The prediction that an increase research employment will result in a concomitant rise an economy's rate of growth is a comparative static prediction for steady-state equilibrium. As such, the prediction relies on other things being equal. However, Caballero and Jaffe (1993) find evidence of declining U.S. research productivity, which may well have gone some way to offset the effect of rising research employment. Furthermore, if an economy is not in steady-state, then the effect of increasing research employment on growth might be offset by diminishing returns to capital accumulation.

Finally, even if there is evidence against the scale effect present in the basic endogenous growth models of Romer (1990) and Aghion and Howitt (1992), it is unclear what conclusion should be drawn. One conclusion is that of Jones (1995b): the exponent on the existing stock of knowledge is less than 1. However, a second conclusion, adopted by Young (1995), is that

---

[34] For example, Nickell (1994) and Blundell, Griffith and Van Reenen (1994) find that rates of productivity growth are related to product market competition, as suggested by the Schumpeterian models of Aghion, Dewatripont and Rey (1995) and Aghion, Harris and Vickers (1995).

[35] See also Barro and Sala-í-Martin (1995a, Chapter 12) and Backus, Kehoe and Kehoe (1992). In general, these studies are beset by the twin problems of the choice of the measure of scale and the unit of observation (for example, with international knowledge spillovers it is unclear that national economies are the relevant unit of observation).

there may well be more than one dimension to technological progress.

Young argues that there may be a variety of differentiated solutions to each technological problem. Implicitly, a distinction is drawn between two dimensions of technological progress: variety and quality. There is an intertemporal spillover in one of these dimensions (quality), but not in the other (variety). At each point in time, the number of varieties of intermediate inputs produced is determined by a free entry condition. Any increase in rents in the research sector, that leaves the cost of quality improvement or the elasticity of demand with respect to quality unaffected, simply results in a proliferation of product variety. This increase in product variety dissipates the original rents in the research sector, leaving the equilibrium rate of quality improvement and the economy's rate of growth unaffected. An increase in scale results in a rise in the *level* of output or utility, but has no effect upon an economy's rate of growth.

Thus, Jones (1995a) evidence of rising research employment may simply reflect a proliferation of the variety of solutions to technological problems, and it becomes unsurprising that there is no effect upon long-run growth. However, the economy's growth rate remains endogenous and any parameter that affects the relative cost or relative demand for quality improvements may affect the economy's rate of growth. Thus, the effect of increasing research employment on an economy's rate of growth may well depend upon the *type of activities* in which those researchers are engaging.

In Chapters 4 and 5, we draw a distinction between *fundamental* innovations (or "major breakthroughs") and *secondary* innovations (the incremental improvements that realise the opportunities latent in each fundamental innovation). To argue that $\phi < 1$ is to argue that the cost of raising the economy's stock of technological knowledge by a given proportion is increasing in that stock of knowledge. This seems plausible for secondary innovations, where the extent of incremental improvement to any one technology may be limited. Indeed, such a specification will be adopted in Chapter 5, where we introduce bounded learning by doing.

However, such an argument seems far less plausible in the case of fundamental innovations or basic research. Whole new lines of research have been opened by discoveries as fundamental as the first law of thermodynamics, general relativity and quantum mechanics. Throughout history, man has tried to define limits to his own knowledge. Each of these attempts has met with failure, and there seems no reason to think that further attempts will not meet with the same degree of success. Throughout the remainder of this thesis, we assume that, at least for fundamental knowledge, the cost of increasing the stock of technological knowledge by a given proportion remains unchanged ($\phi = 1$).

2.7 Conclusion

The two central tenets of this thesis are that technological progress is an important determinant of an economy's rate of economic growth, and that the rate of technological progress is endogenously determined by the intentional choices of profit-seeking agents. This Chapter has surveyed the existing literature on Schumpeterian models of endogenous growth, and distinguished between the variety-based approach of Romer (1990) and the quality-based analysis of Aghion and Howitt (1992).

A central feature of models of endogenous growth through rising product quality is that growth is essentially a process of *creative destruction.* Innovations both destroy the flow of monopoly profits received by incumbent monopolists (value obsolescence), and may also reduce the usefulness of the existing stock of ideas in the research sector (knowledge obsolescence).

The quality ladder approach will serve as the basis for the analysis of much of the rest of this thesis. The present Chapter has assumed that the flow of skilled labour available for research is exogenously determined. In Chapter 3, we extend the analysis to incorporate endogenous investments in human capital or skills. Entrepreneurs' investments in Research and Development (R & D) and workers' investments in human capital exhibit strategic complementarities. As a result, multiple equilibria may exist.

2.8 Appendix

The Bellman equation defining the expected value of an innovation $m+1$ during a unit interval of time is simply

$$V_{m+1} = \pi_{m+1} d\tau + (1 - \rho d\tau)\left[\lambda H^{r}_{m+1} d\tau . 0 + \left[1 - \lambda H^{r}_{m+1} d\tau\right] . V_{m+1}\right],$$

where we use the approximation $e^{-\rho d\tau} \simeq (1 - \rho d\tau)$ for $d\tau$ small. Note: $\lim_{d\tau \to 0} d\tau^2 \simeq 0$.

Hence, as $d\tau \to 0$, the above simplifies to,

$$V_{m+1} = \pi_{m+1} d\tau + V_{m+1} - \left[\lambda H^{r}_{m+1} d\tau + \rho d\tau\right] .V_{m+1},$$

Rearranging and cancelling terms in $d\tau$, we obtain the asset equation in the text,

$$\rho.V_{m+1} = \pi_{m+1} - \lambda.H^{r}_{m+1}.V_{m+1},$$

Chapter 3

Strategic Complementarities Between Human Capital and R & D

3.1 Introduction,[1]

A number of authors have argued that the British Economy suffers from deficiencies in education, skills and training.[2] Finegold and Soskice (1988) argue informally that this deficiency is explained by the fact that Britain is trapped in a "low skills" equilibrium, that is, "a self-reinforcing network of societal and state institutions which interact to stifle the demand for improvements in skill levels."[3] This Chapter will be concerned with two aspects of this network, namely workers' investments in general skills or human capital, and firms' choices of

---

[1] This Chapter is based upon a paper prepared for the 1995 Royal Economic Society Conference: Redding (1996a) "The Low-Skill, Low-Quality Trap: Strategic Complementarities Between Human Capital and R & D." *Economic Journal*, March.

[2] See for example the survey by Keep and Mayhew (1988).

[3] Finegold and Soskice (1988), p. 22.

product quality as mediated by their investments in Research and Development (R & D).

Finegold and Soskice's explanation for the "low skills" equilibrium is somewhat institutional-based. In contrast, we seek to provide a theoretical rationalisation for the existence of a "low skills" equilibrium in a general equilibrium model of endogenous growth. The analysis integrates elements of two strands of the endogenous growth literature, one that has emphasised investments in R & D (see for example Aghion and Howitt (1992) and Romer (1990)) and a second that has emphasised the accumulation of human capital as an engine of growth (see for example Lucas (1988) and Stokey (1991)).

Section 2 considers in greater detail the relationship between R & D, human capital and economic growth. Section 3 extends a version of the "quality ladder" model of growth introduced in Chapter 2 to incorporate endogenous investments in human capital accumulation. Section 4 solves for general equilibrium, while Section 5 evaluates the economy's equilibrium rate of growth. Section 6 examines some policy implications and, in particular, the role for welfare improving R & D and educational subsidies. Finally, Section 7 concludes.

3.2 Research and Development, Human Capital and Economic Growth

As argued in Chapter 1, substantial empirical evidence exists that technological progress is an important determinant of an economy's rate of growth. Most famously, Solow (1957) concluded that 87.5 per cent of the increase in U.S. gross output per man between 1909 and 1949 was unexplained by increases in capital and labour inputs. Of all the explanations for this Total Factor Productivity (TFP) growth, technological progress is perhaps the most plausible.

Thus, a wide range of empirical evidence exists that Research and Development (R & D) expenditures are an important determinant of rates of Total Factor Productivity (TFP) growth.[4] Using firm level data for the U.S., Griliches (1980) estimates that the elasticity of output with respect to R & D is 6 per cent, while using industry-level data for the U.K. Patel and Soete (1988) find an elasticity of 7 per cent. In a more macroeconomic data set including the G7 and 15 other countries, Coe and Helpman (1993) find that both domestic and foreign R & D capital stocks have a significant effect upon an economy's Total Factor Productivity (TFP). Lichtenberg (1992) extends the augmented Solow model considered by Mankiw, Romer and Weil (1992) to include R & D investments, and finds an elasticity of GNP with respect to privately-funded research capital of about 7 per cent.

From a theoretical point of view, one strand of the endogenous growth literature has emphasised profit-seeking Research and Development (R & D) as an engine of steady-state growth. Thus, Chapter 2 surveyed the existing literature of Schumpeterian models, including the variety-based approach of Romer (1990) and the "quality ladder" model of Aghion and Howitt (1992). However, in both the growth through increasing variety and growth through rising quality models, the supply of skilled labour available for research is assumed to be exogenous. In reality, the supply of skilled labour is *endogenously* determined by individuals' investments in education or

---

[4] See Cameron (1996a) for a survey of this literature.

training. The present Chapter extends the quality ladder approach to incorporate endogenous investments in general human capital.[5]

Indeed, a second strand of the endogenous growth literature, including Lucas (1988) and Stokey (1991), has emphasised that human capital accumulation itself may be an engine of steady-state growth. There is some debate in the literature as to whether an economy's growth rate might depend upon the *level* rather than the *rate of growth* of human capital (see for example Benhabib and Spiegel (1994)). However, the present paper follows Lucas (1988) and Stokey (1991) in arguing that it is the rate of accumulation of human capital that is important.

This hypothesis is supported by considerable empirical evidence. In general, empirical evidence takes the form of either growth accounting exercises or regression estimates. A number of authors have sought to extend the growth accounting framework of Solow (1957) to incorporate changes in labour quality or human capital. For example, Jorgensen and Fraumeni (1992) conclude that of the 3.29 per cent average annual growth in value added between 1948 and 1986 in the U.S., 1.31 per cent was explained by physical capital accumulation, 0.23 per cent by increases in labour quality, 0.73 per cent by increases in the quantity of labour and 1.02 per cent by increases in Total Factor Productivity.[6]

In terms of regression evidence, Jenkins (1995) estimates a production function for the

---

[5] Throughout the present Chapter, we assume that an individual's skills may be summarised by a single stock of general human capital h. All investments in human capital are assumed to occur before workers enter the labour force ("in school"), and the terms education, training, skills and human capital will be used interchangeably.

[6] Jorgensen and Fraumeni seek to adjust the U.S. National Accounts to measure the value added of the educational sector. When this adjustment is made, the contribution of labour quality is increased further.

U.K. between 1970 and 1992, using data on the proportion of the workforce possessing various qualifications. A one percentage point increase in highly qualified workers combined with a corresponding one percentage point decrease in the proportion of unqualified workers is estimated to increase output by between 0.42 and 0.63 percentage points. In a cross-section context, Mankiw, Romer and Weil (1992) use secondary school enrolment ratios as a proxy for the rate of human capital accumulation. Using the Summers and Heston (1988) data set, they conclude that, in the transition to steady-state, an increase in secondary school enrolment raises the rate of per capita income growth.

Hence, theoretically and empirically, it seems that *both* Research and Development (R & D) and human capital accumulation affect an economy's rate of growth. However, not only are both forms of investment potentially important for growth, but substantial empirical evidence exists that the incentives to undertake each form of investment are interdependent. Thus, Finegold and Soskice (1988) argue that the incentives to educate and train interact with a whole network of "societal and state institutions," and that as a result an economy may become trapped in a "low skills" equilibrium. Workers investments in human capital and firms' choices of product quality, as mediated by their investments in R & D, constitute two aspects of this network of institutions.

In a microeconomic comparative study of clothing manufacture, Steedman and Wagner (1989) find that British manufacturers are characterised by much longer production runs and fewer changes in product style than their German counterparts. Thus, in Germany the typical length of a production run in women's outerwear is 150-300 garments, while in Britain the figure is in the region of 15000 garments. One of the major explanations proposed for the greater innovativeness of German firms is differences in workforce skills or training: "In the course of their two or three-year training the German machinists had mastered the whole range of operations required for garment making; consequently, when a new style was to be made they needed only a short time (an average of two days) to reach 100 per cent speeds .... Only a small minority of machinists in the British plants visited had mastered more than a few basic operations during their shorter training; not surprisingly, much longer periods (several weeks on average) were required."[7]

More formal econometric evidence is provided by Bartel and Lichtenberg (1987), who estimate labour demand equations for educated and uneducated workers for a panel of 61 U.S. manufacturing industries. Labour demand is derived from a restricted cost function and the productivity of a given technology is assumed to depend upon cumulative production experience. The latter is allowed to enter the restricted cost function in a non-neutral way, so that changes in experience may affect relative factor demand. Bartel and Lichtenberg find that the relative demand for educated workers is decreasing in the age of the capital stock (and hence, it is argued, decreasing in the age of the technology embodied in the capital stock). Educated workers appear to have a comparative advantage in the implementation of new technologies.

---

[7] Steedman and Wagner (1989) p. 49.

This interdependence between human capital accumulation and R & D has received little attention in the existing theoretical literature. Acemoglu (1994) considers a model in which entrepreneurs and workers respectively undertake private investments in physical and human capital in the context of labour market search. A subsection of the paper examines a static choice between two technologies, a case that is similar to Snower (1994) who is concerned with a static choice between skilled and unskilled vacancies.

In this Chapter, we present a model of endogenous growth in which the economy's equilibrium rate of growth depends upon *both* the rate of Research and Development (R & D) and the rate of human capital accumulation. The analysis combines a model of human capital accumulation in the context of labour market search that draws on Acemoglu (1994) with a quality ladder model of R & D that follows Aghion and Howitt (1992). We thus investigate the relationship between investments in human capital and Research and Development (R & D) in an explicitly dynamic context. The two forms of investment exhibit pecuniary externalities and are strategic complements. In the presence of indivisibilities in either the R & D or the human capital accumulation technologies, multiple equilibria may occur. One of these equilibria is interpreted as the "low-skills" equilibrium described by Finegold and Soskice in empirical work.

3.3 The Model

We assume that the world is populated by a sequence of non-overlapping generations. Generations are indexed by t, and each consists of a continuum of workers indexed by l of mass L (normalised to 1) and a continuum of entrepreneurs indexed by i of mass N (normalised to 1). Agents are assumed to live for two periods. Time is indexed by τ, and units of time are chosen such that each period lasts for one unit of time.[8]

3.3.1 Workers

Workers are assumed to be risk neutral, and the lifetime utility a worker of generation t is given by,

$$U_t(c_{1,t}, c_{2,t}) = c_{1,t} + \left(\frac{1}{1+\rho}\right) c_{2,t}, \tag{3.1}$$

where $c_{j,t}$ denotes consumption of generation t in period j, and the interest rate r_t equals the subjective rate of time discount ρ.

At birth, individuals are assumed to inherit a stock of human capital from the preceding generation. This intertemporal spillover of human capital follows Lucas (1988), and the period 1 human capital of each worker l of generation t is given by,

---

[8] In order to simplify notation, we will often suppress an implicit dependence upon time, except where important.

$$h_{1,t}(l) = h_{1,t} = (1-\delta).H_{2,t-1} \tag{3.2}$$

where δ denotes the exogenous rate of depreciation of human capital across generations and $H_{2,t-1}$ is the economy-wide period 2 stock of human capital of generation $t-1$,[9]

$$H_{2,t-1} = \int_0^1 h_{2,t-1}(l)\, dl, \tag{3.3}$$

Workers of each generation may augment their period 2 stock of human capital by devoting a fraction of period 1 to education or schooling. The timing of decisions is assumed to be as follows. At birth, each worker l decides upon the fraction $\nu(l)$, $0 \leq \nu(l) \leq 1$ of period 1 to allocate to schooling or human capital accumulation. Once this decision is made, we assume that each worker is randomly matched one-to-one with an entrepreneur for the duration of their lifetime. Production then occurs for a fraction $(1-\nu(l))$ of period 1 and throughout period 2.[10]

The education production technology is assumed to be as follows. A worker l who devotes a fraction $\nu(l)$ of period 1 to education is assumed to acquire the following period 2 stock of human capital,

$$h_{2,t}(l) = \left(1 + \eta.\nu(l)^{\theta}\right).h_{1,t}, \qquad 0 < \theta < 1, \quad 0 \leq \nu \leq 1, \quad \eta > 0, \tag{3.4}$$

---

[9] In general, we use upper case letters to denote aggregate values, and lower case letters to denote the corresponding values for representative individuals.

[10] Workers are matched with entrepreneurs for the duration of their lifetimes. In terms of Acemoglu (1994), this corresponds to the case of high mobility costs.

where η is an education productivity parameter and θ is the elasticity of period 2 human capital with respect to the fraction of period 1 devoted to education. As a result of the intertemporal spillover noted above, the larger the inherited stock of human capital $h_{1,t} = (1-\delta)H_{2,t-1}$, the more productive investments in human capital accumulation.

3.3.2 Entrepreneurs

Each entrepreneur i is assumed to produce homogeneous final goods output y with the following constant returns to scale production function,

$$y_{j,t}(i) = A_{j,t}(i).h_{j,t}(l), \qquad j = 1, 2, \tag{3.5}$$

where $A_{j,t}(i)$ denotes the productivity or quality of the technology employed by entrepreneur i in period j,[11] and $h_{j,t}(l)$ denotes the period j human capital of the worker l with whom entrepreneur i is matched. We choose final goods output for numeraire, and hence $p_t = 1$ for all t.

Entrepreneurs may invest in uncertain Research and Development (R & D) to raise the quality of final goods output. The timing of decisions is assumed to be as follows. At the beginning of period 1, each entrepreneur i decides upon the fraction $\alpha(i)$ of period 1 output to devote to costly R & D. Research is assumed to take one period and at the end of period 1 all research uncertainty is realised. If research is successful, the entrepreneur enjoys a one-period

---

[11] Quality and productivity are essentially equivalent in the present framework.

patent on the new technology, which may be used in production in period 2. At the end of this period, the patent expires and the research knowledge embodied in it spills over to all entrepreneurs.

It seems plausible that R & D is characterised by large sunk costs and indivisibilities. Hence, following Aghion and Howitt (1994), we will be concerned with the case where the costs of research are fixed. We assume that a fixed fraction α' (where $0 < \alpha' < 1$) of period 1 output is required to produce a research facility. This research facility then yields innovations according to a stochastic production technology. If a fraction $\alpha(i) \geq \alpha'$ of period 1 output is devoted to research, entrepreneur i successfully innovates with probability λ (where $0 < \lambda < 1$). However, for $\alpha(i) < \alpha'$, the probability of research success is zero. The probability $\mu(i)$ that an entrepreneur i innovates at the end of period 1 is thus,

$$\mu(i) = \begin{cases} 0 & \text{if} \quad \alpha(i) < \alpha' \quad \text{where} \quad 0 < \alpha' < 1 \\ \lambda & \text{if} \quad \alpha(i) \geq \alpha' \quad \text{where} \quad 0 < \lambda < 1 \end{cases}, \tag{3.6}$$

Following Aghion and Howitt (1992), we assume that each new technology enables human capital to supply $\gamma > 1$ times as many product services as the previous one. As a result of the spillover of technological knowledge above, all entrepreneurs will employ the same production technology in period 1. Normalising starting quality A_0 to 1, the quality of the period 1 technology employed by entrepreneurs of generation t is given by $A_{1,t} = \gamma^m$, where m denotes the number of innovations that have occurred. Technologies may be thought of as steps on a "quality ladder" and may be indexed by m alone, $m = 0, \ldots, M$, where M denotes the state of the art or highest quality technology. In period 2, technologies will vary across entrepreneurs, according to the distribution of research successes, and we may index the technology of entrepreneur i by $m(i)$.

3.3.3 Wage Determination

Following Acemoglu (1994), workers and entrepreneurs are randomly matched one-to-one so that no entrepreneur or worker remains unemployed. We assume that the surplus from a match is divided between entrepreneurs and workers in the constant proportions $(1-\beta)$ and β respectively.[12] Hence, the flow of income $W_{j,t}(i)$ and the wage per unit of effective human capital $w_{j,t}(i)$ received by an employee l of entrepreneur i in each period $j = 1, 2$ are,

$$\begin{aligned} W_{1,t}(i) &= \beta.A_{1,m}(1-\nu)h_{1,t}, \qquad & w_{1,t}(i) &= \beta.A_{1,m}, \\ W_{2,t}(i) &= \beta.A_{2,m(i)}h_{2,t}(l), \qquad & w_{2,t}(i) &= \beta.A_{2,m(i)}, \end{aligned} \tag{3.7}$$

In period 1, all entrepreneurs i employ the same technology, and $m(i) = m(k) = m$ for all i, k. In period 2, technologies may vary across entrepreneurs, depending on the distribution of research successes. When making their period 1 investments in human capital, workers must form an expectation of their period 2 wage. If matched with an arbitrary entrepreneur i, then, from (3.7) and (3.6), a worker's expected period 2 wage will be given by,

---

[12] This assumption may be justified by for example invoking Nash Bargaining between workers and entrepreneurs. In a different framework, Ulph and Ulph (1994) consider the relationship between union bargaining and a firm's incentive to innovate.

$$\mathsf{E}_{m(i)}\left[w_{2,t}(i)\right] = \beta.\mathsf{E}_{m(i)}\left[A_{2,m(i)}\right] = \beta.\mathsf{E}_{\mu(i)}\left[\mu(i).\gamma + (1-\mu(i))\right].A_{1,t},$$

where the probability of entrepreneur i innovating $\mu(i)$ may take the values 0 or λ, depending upon whether or not she invests in Research and Development (R & D) in period 1. Thus, the expected period 2 wage of a worker matched with entrepreneur i depends upon that entrepreneur's expected period 1 investment in Research and Development (R & D). Since the matching technology is random, there is an equal probability of being matched with each entrepreneur i. Taking expectations across entrepreneurs, each worker's expected period 2 wage is,

$$\mathsf{E}_{m,i}\left[w_{2,t}\right] = \int_0^1 \beta.\mathsf{E}_{\mu(i)}\left[\mu(i).\gamma + (1-\mu(i))\right].A_{1,t}di, \tag{3.8}$$

3.4 General Equilibrium

3.4.1 Workers

Each worker l maximises intertemporal utility (3.1) given the inherited stock of human capital (3.2), the human capital production technology (3.4) and the following intertemporal budget constraint,

$$c_{1,t} + \left(\frac{1}{1+\rho}\right)c_{2,t} \leq w_{1,t}.(1-\nu)h_{1,t} + \left(\frac{1}{1+\rho}\right).\mathsf{E}_{m,i}\left[w_{2,t}\right].h_{2,t}(l), \tag{3.9}$$

where the expected period 2 wage $\mathsf{E}_{m,i}[w_{2,t}]$ is given by (3.8). Under the assumption of risk neutrality, this intertemporal maximisation problem corresponds to choosing $\nu(l)$ to maximise expected discounted lifetime income. Substituting for $c_{j,t}$ in (3.1) using the lifetime budget constraint (3.9), and substituting for $h_{2,t}(l)$, $w_{1,t}$ and $\mathsf{E}_{m,i}[w_{2,t}]$ using (3.4), (3.7) and (3.8), we obtain the following expression for the worker's intertemporal optimisation problem,

$$\max_{\nu(l)} \beta A_{1,m} h_{1,t}. \left[(1-\nu(l)) + \left(\frac{1+\eta.\nu(l)^{\theta}}{1+\rho} \right) . \int_0^1 \mathsf{E}_{\mu(i)} \left[\mu(i).\gamma + (1-\mu(i)) \right] .di \right], \qquad (3.10)$$

where, from (3.2), $h_{1,t} = (1-\delta).H_{2,t-1}$. From the first-order condition to this problem, the equilibrium fraction of period 1 a worker spends accumulating human capital is given by,

$$\nu(l) = \begin{cases} \Lambda \equiv \left[\frac{\theta\eta. \int_0^1 \mathsf{E}_{\mu(i)}[\mu(i).\gamma+(1-\mu(i))].di}{1+\rho} \right]^{\frac{1}{1-\theta}} & \text{for} \quad 0 \leq \Lambda \leq 1 \\ 1 & \text{for} \quad \Lambda > 1 \end{cases}, \qquad (3.11)$$

From equation (3.11), the decision problem facing each worker is symmetric. In equilibrium, all workers make the same first period investment in human capital: the fraction of period 1 the representative worker spends accumulating human capital is given by $\nu(l) = \nu(k) = \nu$ for all l, k. We will be concerned solely with parameter values for which an interior solution $0 < \nu < 1$ exists. Each generation of workers augments the stock of human capital $h_{1,t}$ inherited from the previous generation.[13] The fraction of period 1 spent accumulating human capital is

---

[13] From (3.2) and (3.4), the proportional rate of growth of human capital between two generations is,

independent of the size of this inherited stock. On the one hand, the larger the inherited stock of human capital $h_{1,t}$ the greater the productivity of human capital investments (from (3.4)). On the other hand, the larger $h_{1,t}$ the higher period 1 income in the production sector $W_{1,t} = (1 - \nu(l)).w_{1,t}.h_{1,t}$ and the greater the opportunity cost of making those investments.

Nonetheless, from equation (3.11), the fraction of period 1 spent accumulating human capital ν does depend crucially upon entrepreneurs' expected period 1 investments in Research and Development (R & D), and it is hence to these investments that we now turn.

3.4.2 Entrepreneurs

Given the research technology (3.6), if an entrepreneur i engages in research, she will invest the fixed fraction α' of first period output in R & D. The only decision remaining is whether or not to engage in research. From (3.5) and (3.6), entrepreneur i's expected return from engaging in Research and Development (R & D) if matched with a worker l is given by,

$$V_e^R(i,l) = (1-\beta)A_{1,m}h_{1,t}.\mathsf{E}_{\nu(l)}\left[(1-\alpha')(1-\nu(l)) + \frac{[\lambda.\gamma + (1-\lambda)].\left(1+\eta.\nu(l)^{\theta}\right)}{1+\rho}\right],$$

where $\mathsf{E}_{\nu(l)}\,[\nu(l)]$ denotes the fraction of period 1 worker l is expected to spend accumulating human capital, and where the expected period 2 technology of each entrepreneur i engaging in

---

$$\frac{h_{1,t} - h_{1,t-1}}{h_{1,t-1}} = \eta.\nu^{\theta} - \delta.\left(1+\eta.\nu^{\theta}\right),$$

research is given by $\mathsf{E}_{m(i)}\left[A_{2,m(i)}\right] = \left[\lambda.\gamma + (1-\lambda)\right].A_{1,m}$. Since the matching technology is random, there is an equal probability of being matched with each worker. Taking expectations across workers, entrepreneur i's expected return from investing a fraction α' of first period output in Research and Development (R & D) is thus,

$$V_e^R(i) = (1-\beta)A_{1,m}h_{1,t}.\int_0^1 \mathsf{E}_{\nu(l)}\left[(1-\alpha')(1-\nu(l)) + \frac{[\lambda.\gamma + (1-\lambda)].\left(1+\eta.\nu(l)^{\theta}\right)}{1+\rho}\right] dl, \tag{3.12}$$

Similarly, entrepreneur i's expected return from not investing in Research and Development (R & D) and simply continuing to employ the existing technology is,

$$V_e^0(i) = (1-\beta)A_{1,m}h_{1,t}.\int_0^1 \mathsf{E}_{\nu(l)}\left[(1-\nu(l)). + \left(\frac{1}{1+\rho}\right).(1+\eta.\nu(l)^{\theta})\right] dl, \tag{3.13}$$

Each entrepreneur i's incentive to engage in R & D is given by $V_e^R(i) - V_e^0(i)$, and will be shown to depend crucially upon workers' expected period 1 investments in human capital. From equations (3.12) and (3.13), the decision problem facing each entrepreneur is symmetric. In equilibrium, all entrepreneurs will make the same decision concerning whether or not to engage in Research and Development (R & D): the representative entrepreneur's period 1 investment in R & D will be given by $\alpha(i) = \alpha(k) = \alpha$ for all i, k, and hence $\mu(i) = \mu(k) = \mu$ for all i, k.

Since, in equilibrium, all entrepreneurs make the same period 1 investment in R & D, the representative worker's expected period 2 wage (3.8) may be expressed as,

$$\mathsf{E}_{m,i}\left[w_{2,t}\right] = \beta.\left[\mu_e.\gamma + (1-\mu_e)\right].A_{1,t},$$

where μ_e denotes each worker's expectation of the representative entrepreneur's probability of research success. Hence, from (3.10) and (3.11), the representative worker's period 1 investment in human capital will be as follows,

$$\nu = \begin{cases} \nu_\lambda \equiv \left[\frac{\theta\eta.[\lambda\gamma+(1-\lambda)]}{1+\rho}\right]^{\frac{1}{1-\theta}} & \text{if} \quad \mathsf{E}\left[\alpha\right] \geq \alpha' \\ \nu_0 \equiv \left[\frac{\theta\eta}{1+\rho}\right]^{\frac{1}{1-\theta}} & \text{if} \quad \mathsf{E}\left[\alpha\right] < \alpha' \end{cases}, \tag{3.14}$$

where $\nu_\lambda > \nu_0$. The representative worker's period 1 investment in human capital depends crucially upon the representative entrepreneur's expected period 1 investment in R & D. In equilibrium, all workers devote the same fraction ν of period 1 to human capital accumulation. Hence, from (3.12) and (3.13), the representative entrepreneur's expected returns from investing and not investing in Research and Development (R & D) may be expressed respectively as,

$$V_e^R = (1-\beta)A_{1,m}h_{1,t}.\mathsf{E}_\nu\left[(1-\alpha')(1-\nu) + \left(\frac{1}{1+\rho}\right).[\lambda.\gamma + (1-\lambda)].\left(1+\eta.\nu^\theta\right)\right], \tag{3.15}$$

$$V_e^0 = (1-\beta)A_{1,m}h_{1,t}\mathsf{E}_\nu\left[(1-\nu). + \left(\frac{1}{1+\rho}\right).(1+\eta.\nu^\theta)\right], \tag{3.16}$$

where ν may take the values ν_λ and ν_0 above.

3.4.3 Rational Expectations Equilibrium

We employ the Nash equilibrium solution concept, to solve for a rational expectations equilibrium using (3.2), (3.14), (3.15) and (3.16). On the one hand (from (3.15) and (3.16)), an increase in the representative worker's period 1 investment in human capital ν raises the representative entrepreneur's *average* or expected return from investing in R & D, $V_e^R - V_e^0$.[14] On the other hand (from (3.8)), an increase in the representative entrepreneur's period 1 investment in R & D from 0 to α' raises the representative worker's *average* return from human capital accumulation $\Omega = W_{1,t} + \mathsf{E}_{m,i}\left[W_{2,t}\right]$. Hence, in the present model, the two forms of investment exhibit *pecuniary externalities.*

Similarly, an increase in the representative worker's period 1 investment in human capital ν raises the representative entrepreneur's *marginal* return from investing in R & D. While, an increase in the representative entrepreneur's period 1 investment in R & D from 0 to α' raises the representative worker's *marginal* return from in human capital accumulation. Hence, the two forms of investment are *strategic complements* in the sense of Bulow, Geanakoplos and Klemperer (1985).

Entrepreneurs and workers must make their investments before they enter the labour market. Moreover, as in Acemoglu (1994), labour market search means that the identity of one's

---

[14] From (3.15) and (3.16), it is straightforward to show that $\frac{\partial\left[V_e^R - V_e^0\right]}{\partial\nu} > 0$.

production partner is unknown and ex ante contracts that make one party's investment contingent on the other's are infeasible. The existence of pecuniary externalities between the two forms of investment means that market outcomes need not be socially optimal. Furthermore, in the presence of indivisibilities in the R & D technology, the strategic complementarity between the two forms of investment may induce multiple equilibria.

In a rational expectations equilibrium, agents do not make systematic errors in formulating their expectations. Two such rational expectations equilibria may exist, which we label the "high growth" and "low growth" equilibria respectively.

High Growth Equilibrium

In a high growth equilibrium, workers expect entrepreneurs to invest in R & D, and the resultant increase in their expected wage raises their incentive to invest in human capital. In turn, a larger expected stock of human capital raises the expected returns to investing in R & D relative to those of continuing to employ an existing technology. Hence, entrepreneurs do indeed invest in R & D.

The existence of such an equilibrium may be established in the following way. Suppose that workers expect entrepreneurs to invest in R & D, in which case, $\mu_e = \lambda$. Then, show that if workers have these expectations, it is indeed optimal for entrepreneurs to incur the fixed R & D cost. From (3.14), if $\mu_e = \lambda$, workers human capital investment is given by $\nu = \nu_\lambda$. Suppose that entrepreneurs correctly anticipate workers' human capital investments, then $\mathsf{E}_\nu[h_{2,t}] = \left(1 + \eta.\nu_\lambda^\theta\right).h_{1,t}$. For research to be optimal, we require $V_e^R > V_e^0$, or substituting for $h_{1,t}$ in (3.15) and (3.16), and cancelling common terms,

$$\frac{\lambda.(\gamma - 1)}{1 + \rho} > \frac{\alpha'(1 - \nu_\lambda)}{\left(1 + \eta.\nu_\lambda^\theta\right)}, \tag{3.17}$$

Whenever inequality (3.17) is satisfied, a high growth rational expectations equilibrium exists.

Low Growth Equilibrium

In a low growth equilibrium, entrepreneurs do not find it profitable to invest in R & D and the sole source of growth is human capital accumulation. Workers expect entrepreneurs not to invest in R & D and hence reduce their investments in human capital (relative to a "high growth" equilibrium) accordingly. At this rate of human capital accumulation, the returns to continuing to employ the existing technology exceed those from investing in the development of the next, thereby validating workers expectations.

The existence of a low growth equilibrium may be established in a manner directly analogous to that above. Suppose $\mu_e = 0$, then, from (3.14), $\nu = \nu_0$. For no research to be optimal, we require $V_e^R < V_e^0$. Assuming that entrepreneurs correctly anticipate workers' human capital investments, then $\mathsf{E}_\nu[h_{2,t}] = \left(1 + \eta.\nu_0^\theta\right).h_{1,t}$. Hence, substituting for $h_{1,t}$ and cancelling common terms in (3.15) and (3.16), we require,

$$\frac{\lambda.(\gamma-1)}{1+\rho} < \frac{\alpha'(1-\nu_0)}{(1+\eta.\nu_0^\theta)}, \tag{3.18}$$

Whenever inequality (3.17) is satisfied, a low growth rational expectations equilibrium exists. For a range of parameter values, inequalities (3.17) and (3.18) may be satisfied simultaneously, and hence *multiple equilibria* may exist. Indeed, three cases of the model may be distinguished.

Proposition 1 (a) *If* $\frac{\lambda(\gamma-1)}{1+\rho} > \frac{\alpha'(1-\nu_0)}{(1+\eta.\nu_0^\theta)}$, *there exists a single pure strategy "High Growth" Nash Equilibrium, in which* $\mu = \lambda$ *and* $h_{2,t} = (1+\eta.\nu_\lambda^\theta)h_{1,t}$.

(b) *If* $\frac{\alpha'(1-\nu_0)}{(1+\eta.\nu_0^\theta)} > \frac{\lambda(\gamma-1)}{1+\rho} > \frac{\alpha'(1-\nu_\lambda)}{(1+\eta.\nu_\lambda^\theta)}$, *there exist two pure strategy Nash Equilibria, the "High-" and "Low-growth" Equilibria, characterised by* $\left(\mu = \lambda,\ h_{2,t} = \left(1+\eta.\nu_\lambda^\theta\right).h_{1,t}\right)$ *and* $\left(\mu = 0,\ h_{2,t} = (1+\eta.\nu_0^\theta).h_{1,t}\right)$ *respectively.*

(c) *If* $\frac{\lambda(\gamma-1)}{1+\rho} < \frac{\alpha'(1-\nu_\lambda)}{(1+\eta.\nu_\lambda^\theta)}$, *there exists a single pure strategy "Low Growth" Nash Equilibrium, in which* $\mu = 0$ *and* $h_{2,t} = (1+\eta.\nu_0^\theta).h_{1,t}$.

Proof. See Appendix

The "low-skills" Equilibrium

The high growth equilibrium is characterised by both quality improvements and rapid human capital accumulation, and is interpreted as a "high-skills, high-quality" equilibrium. In contrast, the low growth equilibrium is characterised by no research and a reduced rate of human capital acquisition. The low growth equilibrium is therefore identified with Finegold and Soskice's "low-skills" equilibrium. In the present model, which equilibrium is selected depends entirely upon agents' expectations. For the range of parameter values for which multiple equilibria exist, an economy may become trapped in the "low skills" equilibrium even though a second "high-skills, high-quality" equilibrium exists.

The inequalities (3.17) and (3.18) may be given an intuitive interpretation. $\lambda(\gamma-1)$ is the expected proportional rate of growth of product quality, and $(1+\eta.\nu^{\theta})$ the ratio of the period 2 to the period 1 stock of human capital. From Proposition 1(b), for multiple equilibria to exist, we require $\frac{\alpha'(1-\nu_0)}{(1+\eta.\nu_0^{\theta})} > \frac{\lambda(\gamma-1)}{1+\rho} > \frac{\alpha'(1-\nu_\lambda)}{(1+\eta.\nu_\lambda^{\theta})}$. That is, if workers expect entrepreneurs to invest in R & D, the expected rate of growth of product quality, when discounted, exceeds the period 1 fixed cost normalised by the growth in the stock of human capital across periods. However, if workers expect entrepreneurs to continue to employ the existing technology, this condition is not satisfied.

From the inequality above, multiple equilibria arise for intermediate values of the fixed cost α' and of the size and probability of innovation, γ and λ. Multiple equilibria arise for intermediate parameter values because of the *strategic complementarity* between the two forms of investments on the one hand, and the indivisibility in R & D costs on the other. For R & D to be profitable, we require that workers' investments in human capital are sufficiently large to amortise entrepreneurs' fixed costs of research. In the terminology of Azariadis and Drazen (1990), this constitutes a *threshold externality.*

Proposition 2 *For a "High Growth" Equilibrium to be possible we require either,*

(a) *That the fixed cost parameter α' is sufficiently small,*

(b) *That the size of innovations $\gamma > 1$ is sufficiently large,*

(c) *That the productivity of research λ is sufficiently large,*

(d) *That the subjective rate of time preference ρ is sufficiently small,*

(e) *That the education productivity parameter η is sufficiently large,*

(f) *That the elasticity of human capital with respect to the time spent in education θ is sufficiently large,*

Proof. (a) - (f) all follow from inspection of Proposition 1(a) and (3.14). □

3.5 Steady-State Growth

Having determined equilibrium investments in R & D and human capital accumulation, we now turn to the economy's expected rate of growth. Consider the economy's average or expected rate of growth between two periods of a given generation,[15]

$$\xi_t = \frac{\mathsf{E}_{m,i}\left[Y_{2,t}\right] - Y_{1,t}}{Y_{1,t}} = \frac{\mathsf{E}_{m,i}\left[\int_0^1 A_{2,t}(i).h_{2,t}(i)di\right] - \int_0^1 A_{1,t}(i).h_{1,t}(i)di}{\int_0^1 A_{1,t}(i).h_{1,t}(i)di}, \tag{3.19}$$

In equilibrium, the worker matched with entrepreneur i devotes the same fraction of period 1 to human capital accumulation as all other workers: $\nu(i) = \nu(k) = \nu$ for all i, k. Hence, from

---

[15] In order to simplify notation, we index workers in (3.19) by the entrepreneur with whom they are matched.

equations (3.2) and (3.4), $h_{1,t}(i) = h_{1,t}$ and $h_{2,t}(i) = h_{2,t} = \left(1 + \eta.\nu^{\theta}\right).h_{1,t}$ for all i.

In period 1, all entrepreneurs employ the same production technology and $\int_0^1 A_{1,t}(i)di = A_{1,t}$. In period 2 in contrast, production technologies may vary across entrepreneurs. Since there is a continuum of representative entrepreneurs of mass 1, each of whom innovates with Poisson probability μ, a fraction μ will experience research success at the end of period 1,

$$\mathsf{E}_{m,i} \int_0^1 A_{2,t}(i)di = \left[\mu.\gamma + (1-\mu)\right].A_{1,t},$$

Thus, from (3.19), the economy's expected rate of growth between two periods of a given generation is given by,

$$\xi_t = \left[\mu.\gamma + (1-\mu)\right].\left(1 + \eta.\nu^{\theta}\right) - 1, \tag{3.20}$$

Proposition 3 (**a**) *The economy's average or expected rate of growth in a "high growth" equilibrium is equal to* $\xi_t = \left[\lambda.\gamma + (1-\lambda)\right].\left(1 + \eta.\nu_{\lambda}^{\theta}\right) - 1$.

(**b**) *The economy's average or expected rate of growth in a "low growth" equilibrium is equal to* $\xi_t = \eta.\nu_0^{\theta}$.

Proof. Proposition 3 follows immediately from Proposition 1 and (3.20). □

In contrast to much of the existing endogenous growth literature, the economy's growth rate depends upon *both* the rate of human capital accumulation and upon whether or not entrepreneurs invest in profit-seeking Research and Development (R & D).

Proposition 4 (a) *In both a "low growth" and "high growth" equilibrium, the economy's expected rate of growth is increasing,* (i) *the larger the productivity of education parameter* η*,* (ii) *the greater the elasticity of human capital with respect to time spent in education* θ*,* (iii) *the smaller the subjective rate of time preference* ρ*,*

(b) *In a "high growth" equilibrium, the economy's expected rate of growth is also increasing,* (i) *the greater the productivity of research* λ *and* (ii) *the larger the size of innovations* γ*,*

Proof. (a) and (b) follow from Proposition 3 and (3.14). □

From (3.14), (3.4) and (3.2), the rate of human capital accumulation within a generation is determined partly by η, θ and ρ, and thus each of these parameters has a *direct effect* upon the economy's growth rate in both the "low" and "high" growth equilibria. In addition, the strategic complementarities present in the model mean that η, θ and ρ also affect the relative profitability of R & D and may have an *indirect effect* upon the growth rate.

This indirect effect may be responsible for discrete changes in the economy's rate of growth. Suppose, we begin with intermediate parameter values that sustain multiple equilibria, and expectations co-ordinate upon the "low growth" or "low skills" equilibrium. Then, as for example η and θ rise, the economy's rate of growth will undergo a discrete jump at the parameter values at which the "high growth" equilibrium becomes the unique pure strategy equilibrium.

3.6 Policy Implications

The low-skills equilibrium above is Pareto dominated by its high-skills counterpart. The latter implies both a higher *level* and rate of *growth* of output and National Income. Which of the two equilibria obtains for intermediate parameter values is entirely dependent upon entrepreneurs' and workers' expectations. Hence, as in Cooper and John (1988), there may be a welfare improving role for government policy in *co-ordinating expectations* .

Proposition 5 *A small, temporary subsidy* $s > 0$ *towards the costs of R & D may induce the economy to select the high-skills equilibrium and can be self-financing.*

Proof. See Appendix. □

Traditionally, government subsidies of R & D are justified in terms of a divergence between private and social marginal returns. Proposition 5 provides a slightly different justification in terms of equilibrium selection. In this case, a small subsidy of R & D may have large effects upon both the level and rate of growth of output, and upon agents' welfare. Furthermore, these large effects may be achieved through a temporary subsidy.

A similar welfare improving subsidy of human capital accumulation (education and training) exists, and there is some evidence, albeit inevitably only suggestive, that an implicit subsidy of this form may have played a role in Korea's economic development. Wood (1994) notes that "Korea and Taiwan both greatly raised their literacy rates in the 1950s *prior* to the rapid expansion of labour intensive exports in the 1960s."[16] Indeed the expansion of secondary and higher education was so rapid that "educated unemployment" began to appear (Wood (1994) p. 212). One interpretation of this rise in high-skill unemployment is that the expansion of education was initially in some sense "too rapid" for Korea's state of economic development. Nonetheless, the increase in the supply of skills raised entrepreneurs' incentives to invest in high-technology rather than traditional sectors and products.[17]

However, it is important to note that a rationale for R & D or education subsidies based upon the co–ordination of expectations only exists for the intermediate parameter values for which multiple equilibria exist. In practice, it may be very hard to determine exactly when this is the case.

3.7 Conclusion

The present Chapter has sought to provide a rationalisation for the existence of a "low skills" equilibrium in a general equilibrium model of endogenous growth. The analysis has been concerned with two aspects of the "network of societal and state institutions," which, according to Finegold and Soskice (1988), "interact to stifle the demand for improvements in skill levels." These two aspects are workers' investments in general human capital on the one hand and firms' investments in Research and Development (and hence product quality) on the other.

---

[16] Wood (1994) p. 7 (my italics).

[17] Redding (1996b) considers economic development as a process of structural transformation. The concept of strategic complementarity is used to derive necessary and sufficient conditions for a low-level development trap to occur.

The "quality ladder" model of growth developed in Chapter 2 was extended to endogenise the supply of skilled labour. As such, the analysis has sought to integrate two strands of the endogenous growth literature, one that has emphasised R & D and a second that has emphasised human capital accumulation as an engine of growth. However, the point is not just that both forms of investment affect an economy's rate of growth but that the incentives to undertake each are interdependent.

Investments in R & D and human capital exhibit *pecuniary externalities* and are *strategic complements.* If the R & D technology is characterised by indivisibilities, then, for intermediate parameter values, this strategic complementarity results in the existence of multiple equilibria. In one of these equilibria, workers' investments in human capital are sufficiently large so as to amortize the fixed cost of R & D, while in the other R & D remains unprofitable.

One of these equilibria may be interpreted as the "low-skills" equilibrium described by Finegold and Soskice (1988). The "high-skills" equilibrium Pareto dominates its "low-skills" counterpart, and an economy in a "low-skills" equilibrium enjoys a lower *level* and *rate of growth* of per capita income. Which equilibrium is selected depends entirely upon agents' expectations, and a potential role emerges for government policy in *co-ordinating expectations.* This justification only exists for intermediate parameter values. However, there is some suggestive evidence that the public policies towards education pursued in Korea might be justified in these terms.

3.8 Appendix

3.8.1 Proof of Proposition 1

(a) Suppose the contrary is true, namely $\mu_e = 0$. Workers' period 1 investments in human capital $\nu(l) = \nu(k) = \nu$ are given by ν_0 in (3.14). Substituting for ν_0 in (3.4) and using (3.2), we obtain $h_{2,t} = (1 + \eta.\nu_0^\theta).(1 - \delta)H_{t-1}$. If entrepreneurs correctly anticipate workers' period 1 investments in human capital, $\mathsf{E}_\nu[h_{2,t}] = h_{2,t}$. However, from (3.15) and (3.16), for the parameter values imposed in the Proposition, $V_e^R > V_e^0$. Hence, R & D is profitable $\mu = \lambda$, and $\mu_e = 0$ is not a rational expectations equilibrium.

(b) Suppose $\mu_e = 0$. Then, from (3.14), (3.2), (3.4), (3.15) and (3.16), for the parameter restrictions imposed in the Proposition, $V_e^R < V_e^0$. However, suppose $\mu_e = \lambda$. Then, $V_e^R > V_e^0$.

(c) Suppose the contrary is true and entrepreneurs are expected to invest in R & D, $\mu_e = \lambda$. Then, from (3.14), (3.2), (3.4), (3.15) and (3.16), for the parameter restrictions imposed in the Proposition, $V_e^R < V_e^0$. Hence, R & D is unprofitable $\mu = 0$, and $\mu_e = \lambda$ is not a rational expectations equilibrium. □

3.8.2 Proof of Proposition 5

Suppose that $\frac{\lambda(\gamma-1)}{1+\rho} = \frac{\alpha'(1-\nu_0)}{(1+\eta.\nu_0^\theta)}$ and a "low-skills" equilibrium is just feasible. Since $\nu_\lambda > \nu_0$, $\frac{\lambda(\gamma-1)}{1+\rho} > \frac{\alpha'(1-\nu_\lambda)}{(1+\eta.\nu_\lambda^\theta)}$ and a "high-skills" equilibrium is also feasible.

Consider a small proportional *rate* of subsidy of the costs of R & D, $s > 0$. The private costs of R & D are now given by $(\alpha' - s).y$, where the total cost of the subsidy is $S = s.y$. By assumption $\frac{\lambda(\gamma-1)}{1+\rho} > \frac{(\alpha'-s)(1-\nu_0)}{(1+\eta.\nu_0^\theta)}$ and the "low-skills" equilibrium can no longer be supported. The "high-skills" equilibrium becomes the unique pure strategy equilibrium.

Suppose the subsidy is financed by a proportional rate of tax ϕ, $0 < \phi < 1$, on entrepreneurs' profits. This tax is levied irrespective of whether the entrepreneur engages in R & D or not and hence does not affect the decision to undertake R & D. In equilibrium, all firms undertake R & D, and, for the subsidy to be self-financing, we require, $\phi.V^R \geq S$. That is, from (3.15), rearranging and cancelling terms, we require,

$$\phi.(1-\beta)\left[\begin{array}{c}(1-\alpha')(1-\nu_\lambda)+\\ \left(\frac{1}{1+\rho}\right)[\lambda\gamma+(1-\lambda)](1+\eta.\nu_\lambda^\theta)\end{array}\right] \geq s.(1-\nu_\lambda)\left[1-\phi.(1-\beta)\right],$$

As $s \to 0$, this inequality must be satisfied. The subsidy need only be temporary. Once it is removed, then, as long as neither the entrepreneur's nor workers' expectations change, the economy will remain at the "high-skills" equilibrium. □

Chapter 4

Fundamental and Secondary Innovation

4.1 Introduction

Chapters 2 and 3 have considered models in which the economy's long-run rate of growth is endogenously determined by profit-seeking investments in Research and Development (R & D). In the models of both Chapters, the discovery of a new idea in the research sector (*invention*) is followed immediately by its implementation in the intermediate input sector (*innovation*). Once the idea is adopted in intermediate input production, it is then assumed that the full productive potential of the innovation may be realised instantaneously and costlessly.

In reality, innovation may follow some time after invention, and, as we shall see in later Chapters, it may not be profitable to adopt some inventions in the production sector at all. Furthermore, considerable evidence exists that the full productive potential of an innovation is not realised until after a lengthy process of further improvement. Young (1993a) cites the example of the steam engine,

> "Thus, the steam engine, even after the invention of the separate condenser by James Watt in 1765, was still merely a crudely engineered piston, which was principally used as a water pump in mines. At that point in time, it posed no threat whatsoever to the dominance of the water wheel in the provision of power. Only after John Wilkinson's boring mill (in 1776) eliminated gaps between pistons and cylinders (which had previously been stuffed with rags) and William Murdock's sun and planet gearing system (in 1781) provided a means of converting vertical motion in rotary force did the steam engine become a generally useful source of power."[1]

Learning by doing may be extremely important in realising the productive potential of an innovation, and in the following we review some evidence to this effect. More generally, the recognition that the productivity of technology is dependent upon a process of further improvement leads to a distinction between two dimensions of innovation. Following Aghion and Howitt (1996a), we may distinguish between *fundamental* and *secondary* innovations. *Fundamental* innovations constitute "major breakthroughs," such as the steam engine or the internal combustion engine, which open up whole new areas for further productivity improvement. The opportunities latent in each fundamental innovation are then realised through a sequence of *secondary* innovations or minor improvements. Thus, in the case of the steam engine, examples of secondary innovations would be the boring mill and the sun and planet gearing system.

The distinction between fundamental and secondary innovation will be important in Chapter 5, where we investigate the question whether there is a "penalty" to being a pioneer of a technology. The purpose of the present Chapter is to survey the existing literature on Schum-

---

[1] Young (1993a), pp. 446.

peterian models in which an explicit or implicit distinction between different dimensions of innovation exists. Section 2 is concerned with the role of learning by doing as a source of productivity improvement for new technologies. We begin by reviewing the analysis of Young (1991), in which the potential for learning by doing in any one good is limited or bounded, but in which spillovers of learning by doing across goods result in endogenous growth. Young (1991) does not constitute a Schumpeterian model of endogenous growth, in so far as the introduction of new technologies is a serendipitous by-product of production activity. The model is of importance because it serves as the basis for the analysis of Young (1993a), in which the discovery of new technologies is the result of purposive research and the productivity of these technologies is then gradually realised through a process of bounded learning by doing.

Section 3 considers explicitly the idea that one may draw a distinction between different dimensions of innovation. Following Aghion and Howitt (1996a), we distinguish fundamental innovation from secondary innovation. The former is identified with the *research* component of R & D and the latter with the *development* component. In Aghion and Howitt (1996a), both forms of innovation are the result of intentional choices by profit-seeking agents. We review the determinants of the equilibrium allocation of resources between research and development, and of the economy's rate of growth. Finally, Section 4 concludes.

4.2 Learning by Doing

In Chapter 1, we defined a technological innovation as any change in the organisation of production that results in either a reduction in production costs, an improvement in product quality or the introduction of new goods. In the present Section, we consider the hypothesis that experience in the production of a good may itself be a source of such organisation change: a phenomenon referred to as *learning by doing.*

A considerable body of evidence from a wide range of different industries suggests that production experience may be an important source of improvements in the productivity of a given technology. Arrow (1962) cites evidence collected by Wright (1936) for airframe production, where the amount of labour required to produced the N^{th} airframe of a given type was found to be proportional to $N^{-1/3}$. Similarly, Lucas (1993) cites case study evidence compiled by Searle (1945) and Rapping (1965) for the production of the "Liberty Ship" in 14 U.S. shipyards during World War II. Each doubling of cumulative output was found to reduce the number of man-hours required per ship by between 12 and 24 per cent.[2]

In each case, the accumulation of production experience is not only an important source of innovation, but appears to be subject to diminishing returns. Thus, in order to reduce unit labour requirements for Liberty Ships by 12 to 24 *per cent*, one was required to *double*

---

[2] For more recent evidence, see Foster and Rosenzweig (1995), who consider the adoption of high-yielding seed varieties (HYVs) in India. The latter found that a doubling of own prior experience with a HYV (defined in terms of hectares cultivated) was found to increase mean profits by 21 per cent. See also Bahk and Gort (1993) for evidence from new manufacturing plants in the U.S. over the period 1973-1986.

cumulative output. It appears that, in the words of Arrow (1962), " ... learning associated with the repetition of essentially the same problem is subject to sharply diminishing returns."[3]

In Arrow (1962), technological change is embodied in new vintages and the production process associated with any given capital good is characterised by fixed coefficients. However, the amount of labour η required to produce a unit of output with a given capital good is assumed to depend upon cumulative gross investment G at the time the capital good is produced, $\eta = \eta(G)$. This reflects learning by doing, and unit labour requirements are assumed to take the form $\eta(G) = b.G^{-\alpha}$ (where $b > 0$, $\alpha > 0$). In light of the empirical evidence discussed above, Arrow is largely concerned with the case $0 < \alpha < 1$.

d'Autumne and Michel (1993) show that endogenous growth is possible in Arrow's model if there are constant or increasing returns to the accumulation of production experience: that is, if $\alpha \geq 1$. In this case, the analysis is somewhat similar to Romer (1986). However, as argued above, the empirically plausible case is where learning by doing is characterised by diminishing returns, in which case the economy's growth rate remains exogenous. Young (1991) considers an alternative specification, where there are constant returns to learning by doing for a range of values of production experience, but where there is a lower bound to the unit labour requirements that may be attained for each good. Although learning by doing is *bounded* in any one good, endogenous growth results because (as in Stokey (1988)) spillovers of learning by doing lead to the introduction of new goods.

---

[3] Arrow (1962), pp. 155.

4.2.1 Bounded Learning by Doing (Young (1991))

Young (1991) considers an economy where the number of goods for which technological blueprints already exist is infinite at each point in time τ. Goods are indexed by their degree of technological sophistication $m \in [0, \infty)$, with the production of higher numbered goods involving more advanced technologies. Skilled labour H is the sole factor of production, and Young (1991) assumes that, for each good m, there is a lower bound on *potential* unit labour requirements $\bar{a}(m)$. $\bar{a}(m)$ is assumed to be non-increasing in m, so that more sophisticated goods are characterised by either lower or the same *potential* unit labour requirements. For simplicity, we consider the case where $\bar{a}(m)$ takes the form,

$$\bar{a}(m) = \bar{a}.e^{-m}, \tag{4.1}$$

However, *actual* unit labour requirements are given by $a(m, \tau)$, where $a(m, \tau)$ is assumed to be continuous in m and $\lim_{m \to \infty} a(m, \tau) = \infty$. Although Young (1991) considers a very general specification, for simplicity, we restrict the analysis to the specific functional form considered in a Section of the paper. Suppose that at some arbitrary time $\tau = 0$, there exists a good N such that, for all goods $m \leq N(0)$, the potential for learning by doing has been exhausted. As a result, actual unit labour requirements equal potential. For all goods $m > N(0)$, *actual* unit labour requirements are exponentially increasing in the technological distance between m and $N(0)$. Thus, as illustrated in Figure 1, unit labour requirements at time $\tau = 0$ are given by,

$$a(m,0)=\begin{cases}\bar{a}.e^{-m} & \text{for all} \quad m\leq N(0)\\ \\ \bar{a}.e^{-N(0)}.e^{m-N(0)} & \text{for all} \quad m>N(0)\end{cases}, \tag{4.2}$$

$N(0)$ denotes the most sophisticated good for which the potential for learning by doing has been exhausted at time 0. As will be seen below, if unit labour requirements are initially symmetric around $N(0)$, they will remain symmetric around an ever increasing $N(\tau)$ for all $\tau \geq 0$. $N(\tau)$ may be thought of as summarising the state of *technological* knowledge.

For those goods for which potential unit labour requirements have not been attained, actual unit labour requirements are assumed to fall as a result of learning by doing. The rate of learning by doing depends upon the economy-wide flow of skilled labour devoted to final goods production. Production knowledge *spills over* across all goods where the potential for productivity improvement still exists, and learning by doing takes the form of an economy-wide externality. Specifically, Young (1991) assumes that the most sophisticated good for which all potential for learning by doing has been exhausted evolves according to,

$$\frac{dN(\tau)}{d\tau}=\int_{N(\tau)}^{\infty} H^{p}(m,\tau)dm, \tag{4.3}$$

where $H^p(m,\tau)$, $0 \leq H^p(m,\tau) \leq H$, denotes the flow of skilled labour devoted to the production of good m at time τ. As shown in Figure 1, $N(\tau)$ rises over time, and it is indeed the case that, at each point in time $\tau \geq 0$, unit labour requirements remain symmetric around a good $N(\tau)$.

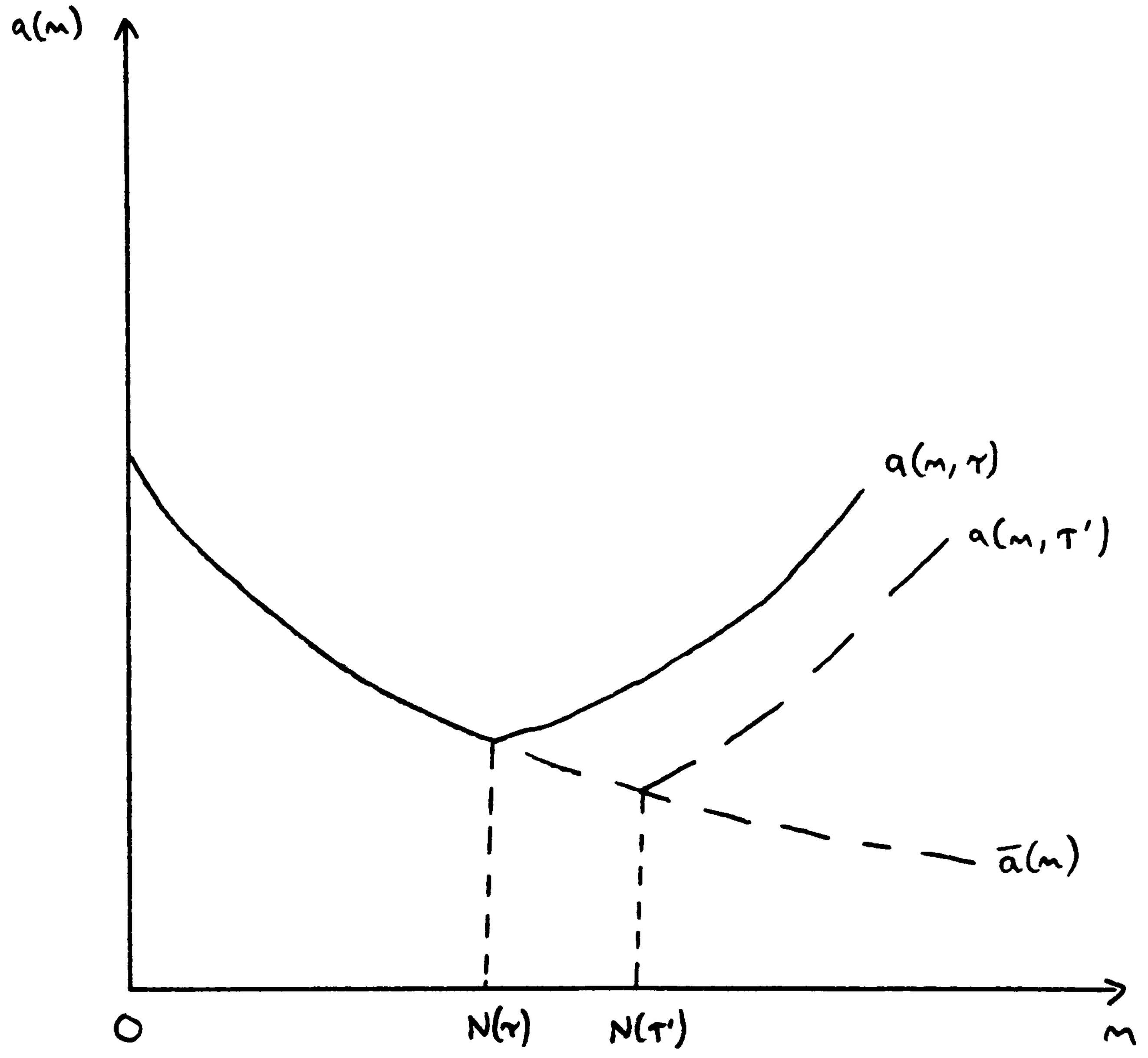


Figure 1: Actual and Potential unit labour requirements.

Consumer preferences are assumed to be intertemporally additive separable, with instantaneous utility additive separable and logarithmic in the consumption of each good,

$$U_\tau = \int_\tau^\infty e^{-\rho(t-\tau)}.\int_0^\infty \log\left[c(m,t)+1\right] dm\ dt, \tag{4.4}$$

where ρ denotes the subjective rate of time preference. Under the specification in (4.4), consumers exhibit a desire for a variety of goods, and the present model thus combines elements of horizontal as well as vertical differentiation.

We assume that there is no storage technology, and the representative consumer's optimisation problem corresponds to allocating her consumption across goods m to maximise instantaneous utility. The output of each good m is given by $y(m,\tau) = a(m,\tau).H^p(m,\tau)$. Each good is produced under conditions of perfect competition, and hence bears a price of $p(m,\tau) = a(m,\tau).w$, where w is the skilled wage. In instantaneous equilibrium, we require that, for all goods m and z consumed in positive quantities, their relative price equals minus the marginal rate of substitution between the two goods. That is, from the above,

$$\frac{1}{[c(m)+1].a(m)} = \frac{1}{[c(z)+1].a(z)} \tag{4.5}$$

At each point in time τ, there exists a good $\underline{m}(\tau)$ such that, for all goods m for which $a(m) < a(\underline{m})$ consumption is positive, while for all goods z for which $a(z) \geq a(\underline{m})$ consumption is zero. From the above, unit labour requirements are symmetric around $N(\tau)$. Hence, there exists a second good $\overline{m}(\tau)$, $\overline{m} > \underline{m}$, that is located the same distance from $N(\tau)$ as $\underline{m}(\tau)$, for which $a(\overline{m}) = a(\underline{m})$ and the same is true. Instantaneous equilibrium is shown in Figure 2, and the representative agent consumes the set of goods $m \in (\underline{m}(\tau), \overline{m}(\tau))$. Learning by doing reduces unit labour requirements on all goods $m > N(\tau)$ produced in positive amounts, enabling ever more sophisticated goods to be consumed.

4.2.2 Invention and Bounded Learning by Doing (Young (1993a))

In Young (1991), it is assumed that there exist an infinite number of technological blueprints, freely available to the production sector. The blueprints for more sophisticated goods are initially characterised by higher actual unit labour requirements. However, spillovers of learning by doing reduce actual unit labour requirements and lead to the introduction of ever more sophisticated varieties of goods over time.

Young (1993a) extends the analysis to allow the discovery of blueprints for new varieties of goods to be the result of intentional investments in Research and Development (R & D). Young considers an economy where, at an arbitrary time $\tau \geq 0$, technological blueprints only exist for a set of goods $m \in [0, M(\tau)] \subseteq \Re_{+}$. $M(\tau)$ denotes the most sophisticated good that society knows how to produce at time τ, and characterises the state of *scientific* knowledge. The production sector is exactly as before. $N(\tau)$ denotes the most sophisticated good for which all potential for learning by doing has been exhausted, and characterises the state of *technological* knowledge.

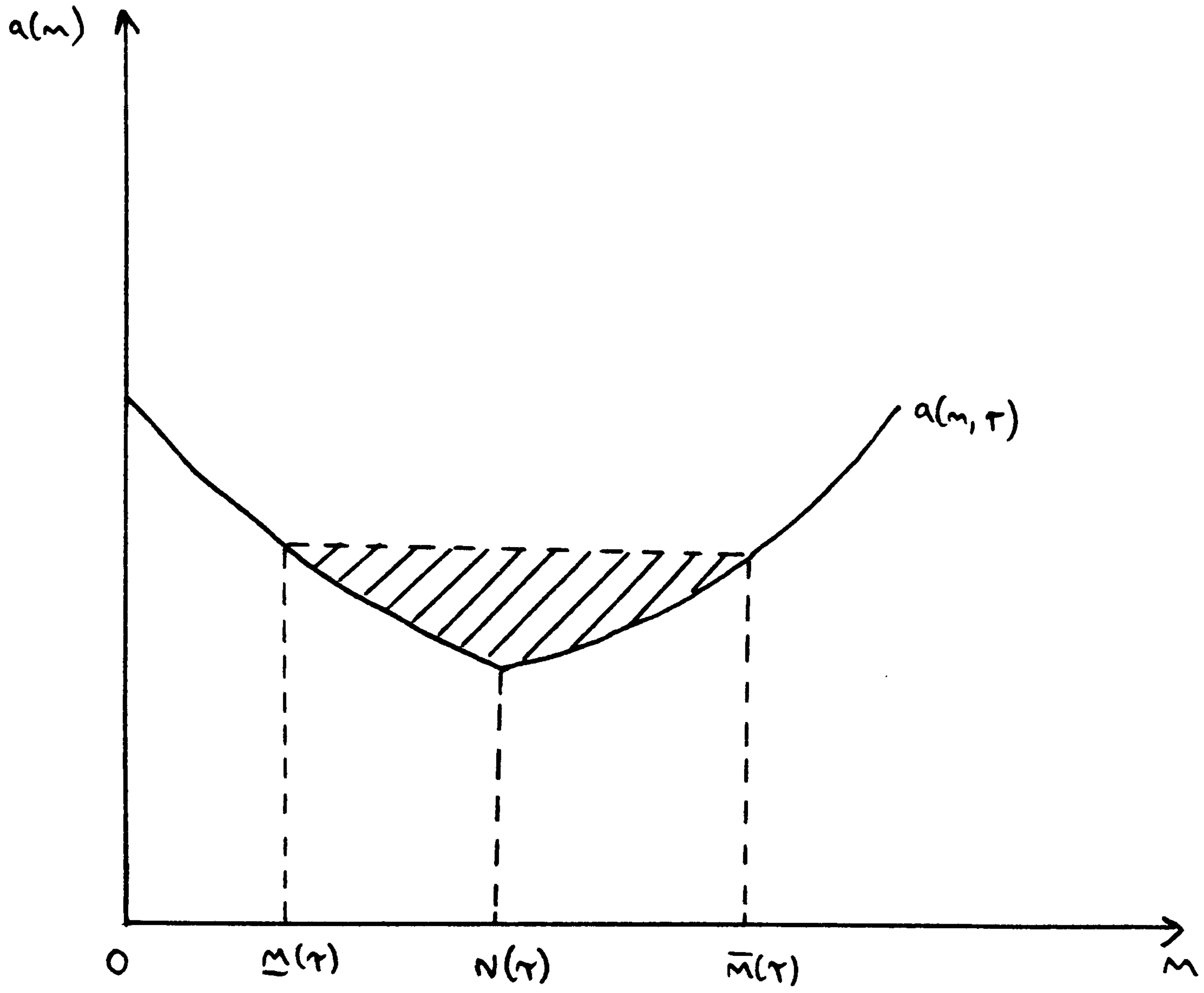


Figure 2: Instantaneous Equilibrium at time τ.

Skilled labour is the sole factor of production, and may be used either in current production or in Research and Development (R & D). The research sector produces technological blueprints for new varieties of goods, and $M(\tau)$ evolves according to,

$$\frac{dM(\tau)}{d\tau} = \frac{H^r}{a_r}, \tag{4.6}$$

where $a_r > 0$ parameterises the productivity of research and H^r denotes the flow of skilled labour employed in research. Researchers receive an infinitely-lived patent for every good they invent, which they may then either sell to the production sector or choose to implement themselves. In the production sector, the owner of each patent engages in monopolistic competition with all other patent holders.

The representative consumer's preferences are assumed be intertemporally additive separable. Instantaneous utility exhibits a strong but not unbounded desire for a variety of goods, and is defined as the logarithm of the functional $u\{c(\cdot,\tau)\}$,

$$U_\tau = \int_\tau^\infty e^{-\rho(t-\tau)}.\log\left[u\{c(\cdot,t)\}\right]dt, \tag{4.7}$$

where ρ denotes the subjective rate of time preference and,

$$u\{c(\cdot,\tau)\} = \int_0^{M(\tau)} ||c(\tau)||\, g\left(\frac{c(m,\tau)}{||c(\tau)||}\right) dm, \tag{4.8}$$

$$||c(\tau)|| = \int_0^{M(\tau)} c(m,\tau)dm,$$

$g(\cdot)$ is assumed to be continuously differentiable, with $g(0) = 0$ and $g'(0) < \infty$. A bounded desire for variety is manifested in the assumption that $g(\cdot)$ is strictly concave and in the restriction on $g'(0)$.

Since preferences are intertemporally additive separable, the representative consumer's optimisation problem may be solved in two stages. Firstly, consumers choose the time profile of expenditure $E(\tau)$ to maximise intertemporal utility subject to the intertemporal budget constraint. Given the logarithmic form of consumer preferences (4.7), the optimal time profile of expenditure satisfies,

$$\frac{\dot{E}(\tau)}{E(\tau)} = r(\tau) - \rho, \tag{4.9}$$

where $r(\tau)$ denotes the interest rate in the riskless consumption loans market. Secondly, at each point in time, consumers allocate their expenditure across goods m to maximise instantaneous utility, given instantaneous expenditure $E(\tau)$. Since the representative consumer's demand for variety is bounded, goods may or may not be produced immediately after they have been discovered. As a result, a distinction emerges between *invention* (the discovery of new technological blueprints) and *innovation* (the adoption of a blueprint in the production sector).

The equilibrium rate of R & D is determined by a free entry condition relating the rate of

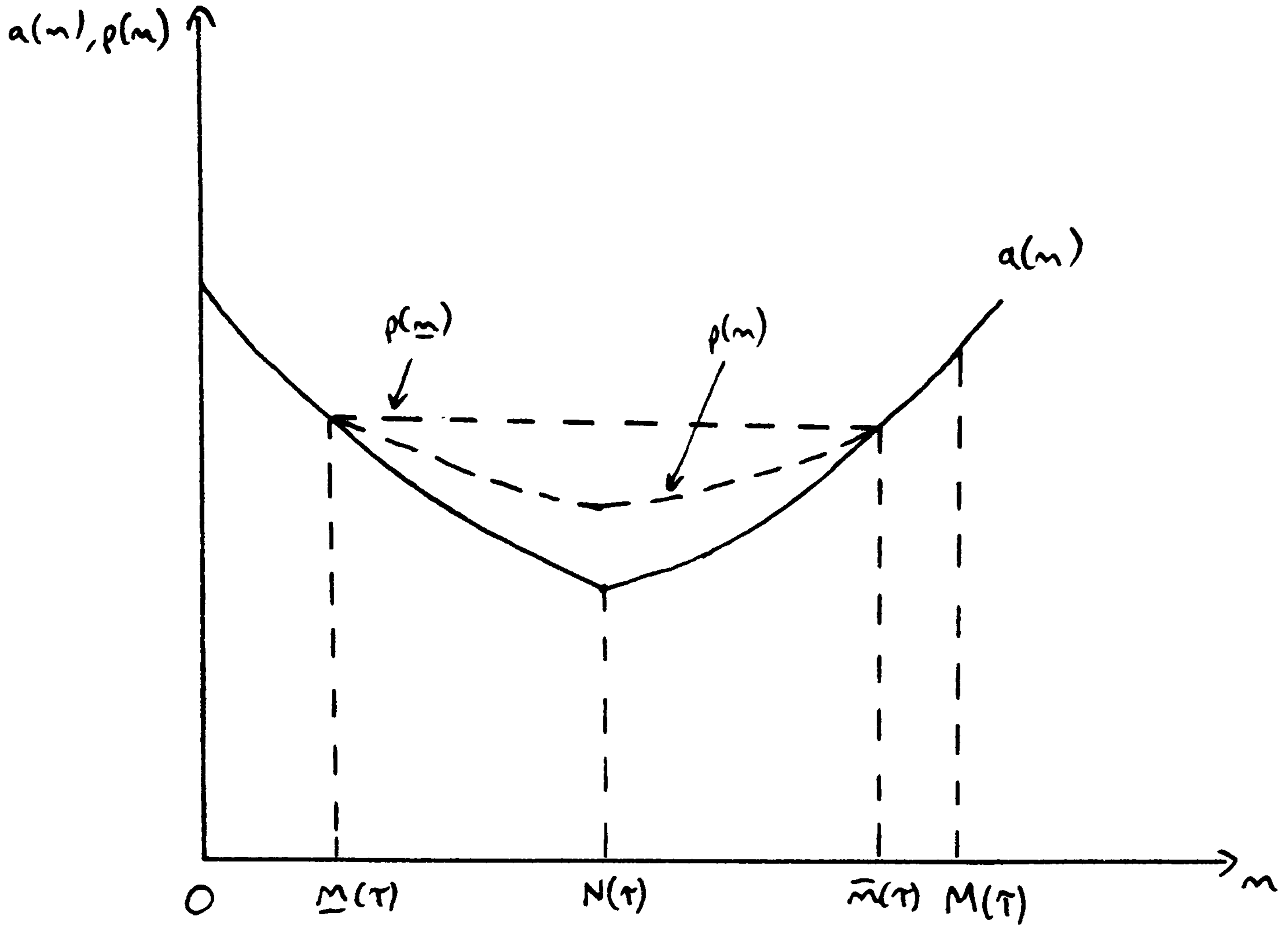


Figure 3 : Instantaneous equilibrium where there is a lag between the discovery of a good (invention) and its production (innovation)

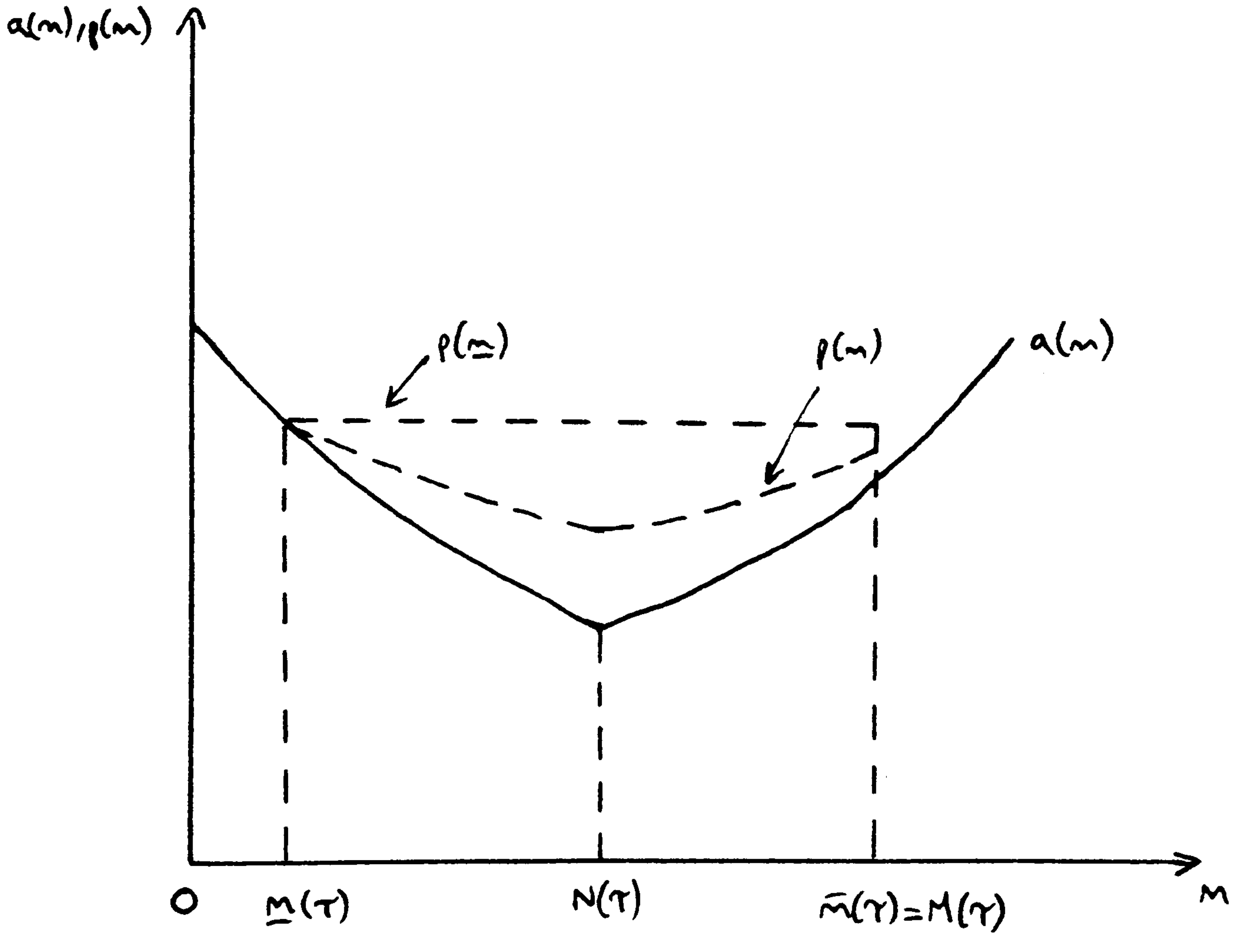


Figure 4 : Instantaneous equilibrium where once a good has been discovered it is immediately produced in positive quantity.

return in the research sector to the riskless rate of return in the consumption loans market. There exist two types of steady state equilibrium characterised by a positive rate of growth. Firstly, as shown in Figure 3, consumers' demand for variety may be insufficient to ensure that goods are produced immediately after they are discovered. In this case, the constraint upon the economy's growth rate is the rate of learning by doing, which determines the rate at which inventions are implemented in the production sector. Secondly, if consumers' demand for variety is sufficiently large, then a good will be produced in positive quantity immediately after it is discovered. In this case, as shown in Figure 4, the constraint upon the economy's growth rate is the rate of discovery of new technological blueprints. That is, the rate of Research and Development (R & D).

4.3 Fundamental and Secondary Innovation

The analysis of Young (1993a) is important because it is a Schumpeterian model of endogenous growth, which successfully captures the idea that the realisation of the productive potential of a technology is dependent upon a process of further innovation. This idea suggests that, more generally, one might distinguish between at least two dimensions of technological progress. Following Aghion and Howitt (1996a), we distinguish *fundamental* innovations from the *secondary* innovations that realise the opportunities latent in each fundamental technology. While fundamental innovations are "major breakthroughs," such as the steam engine, secondary innovations are more minor improvements to a given technology, such as the boring mill or the sun and planet gearing system in the case of the steam engine.[4]

A number of authors have made related distinctions. Bresnahan and Trajtenberg (1992) and Helpman and Trajtenberg (1994) distinguish *General Purpose Technologies (GPTs)* (such as the steam engine, electricity or micro-electronics) from the complementary advances that develop these technologies. Amable (1993) contrasts *radical* and *incremental* innovation, while Jovanovic and Rob (1990) compare *intensive* with *extensive* search. Finally, Dosi (1982) and Redding (1994) differentiate between *technological paradigms* and the *technological trajectories* that each creates.

Although Young (1993a) does not explicitly draw a distinction between fundamental and secondary innovation, the analysis may clearly be interpreted in these terms. The distinction between different dimensions of innovation is important, because the extent of secondary innovation associated with one fundamental technology may well affect the incentive to engage in research directed at the discovery of the next. This issue will be the concern of Chapter 5, where we investigate the sense in which there may be a "penalty" to being a pioneer of one production technology.

The model of Chapter 5 will be Schumpeterian in the sense that the introduction of new fundamental technologies is the result of purposive research. However, given the wide range of evidence that learning by doing is important in realising the productive potential of a technol-

---

[4] Of course, in principle there might be higher dimensions of innovation. The productive potential of each secondary innovation might be realised through a sequence of even more minor innovations. For simplicity, we restrict consideration to the two-dimensional case.

ogy, we follow Young (1993a) in assuming that secondary innovation takes the form of learning by doing. In general, both fundamental and secondary innovation may be the result of intentional choices by profit-seeking agents. This is the case in Aghion and Howitt (1996a), where fundamental innovation is the result of investments in *research* and secondary innovation the result of corresponding investments in *development.* Before turning to the penalty of a pioneer, we review the analysis of Aghion and Howitt (1996a), and the determinants of the equilibrium allocation of resources between research and development.

4.3.1 Fundamental Research and Secondary Development (Aghion and Howitt (1996a))

Aghion and Howitt (1996a) consider an economy populated by continua of infinitely lived skilled workers $h \in [0, H]$ and unskilled workers $l \in [0, L]$. Time is continuous, and is indexed by τ. The economy is composed of four sectors: final goods, intermediate inputs, research and development. Homogeneous final goods output is produced in a sequence of *product lines* of different vintages, using intermediate inputs that are specific to each product line. Intermediate inputs are produced with unskilled labour. The introduction of new product lines (*fundamental* innovation) is the result of research. Development is specific to each product line, and produces blueprints for new varieties of intermediate inputs (*secondary* innovation). Skilled labour is employed in both research and development.

Consumer preferences

Skilled workers and unskilled labourers are assumed to have identical preferences, which are intertemporally additive separable. Instantaneous utility is linear in the representative agent's consumption c of the output Y of a homogenous final good,

$$U_\tau = \int_\tau^\infty e^{-\rho(t-\tau)} c_\tau dt, \tag{4.10}$$

Consumers are thus risk neutral, and the interest rate r_τ equals the subjective rate of time preference ρ. Each skilled worker is endowed with one unit of skilled labour, and each unskilled worker one unit of unskilled labour. Both are supplied inelastically with zero disutility.

The Structure of Knowledge

Aghion and Howitt (1996a) distinguish three different types of knowledge: fundamental, secondary and general. As argued above, *fundamental* innovations are the result of *research* and open up new product *lines*. These product lines are then *developed* by a *sequence* of secondary innovations that take the form of technological blueprints for a specific product or intermediate input in that line. An example of a fundamental innovation might thus be the laser, which has been developed through a sequence of blueprints for specific products such as compact disk players and laser scalpels.

The productivity of each fundamental line discovered at time τ is assumed to depend upon the state of *general* knowledge at that time. General knowledge may be generated both by *research* and *development*, and is introduced to capture the idea that many of the productivity improvements wrought by fundamental innovations may be an unintentional by-product of development activities rather than the intentional outcome of research.

Production

If we denote the stock of general knowledge at time τ by A_τ, then the flow of final goods output produced from a line of vintage v of time $\tau \geq v$ is given by,

$$Y_{\tau,v} = S_{\tau,v}.A_v B(l_{\tau,v}), \tag{4.11}$$

where $S_{\tau,v}$ denotes the number of intermediate inputs developed for lines of vintage v by time $\tau \geq v$. Unskilled labour l is used to produce intermediate inputs, and each intermediate input produced in a line of vintage v at time $\tau \geq v$ is assumed to yield a flow of output $A_v.B(l_{\tau,v})$. Integrating over vintages of lines, we obtain aggregate final goods output at time τ,

$$Y_\tau = \int_{-\infty}^{\tau} S_{\tau,v}.A_v B(l_{\tau,v}) dv, \tag{4.12}$$

The flow of output across lines is illustrated in Figure 5. Fundamental innovations result in the introduction of new vintages. The flow of output from a line of a given vintage v depends upon the state of general knowledge at its time of discovery, the number of blueprints for intermediate inputs developed by time $\tau \geq v$ and the flow of unskilled labour devoted to the manufacture of each intermediate input. As new lines are introduced, unskilled labour and skilled labour are gradually reallocated from old lines to new. Hence, output is decreasing in old lines and increasing in new.

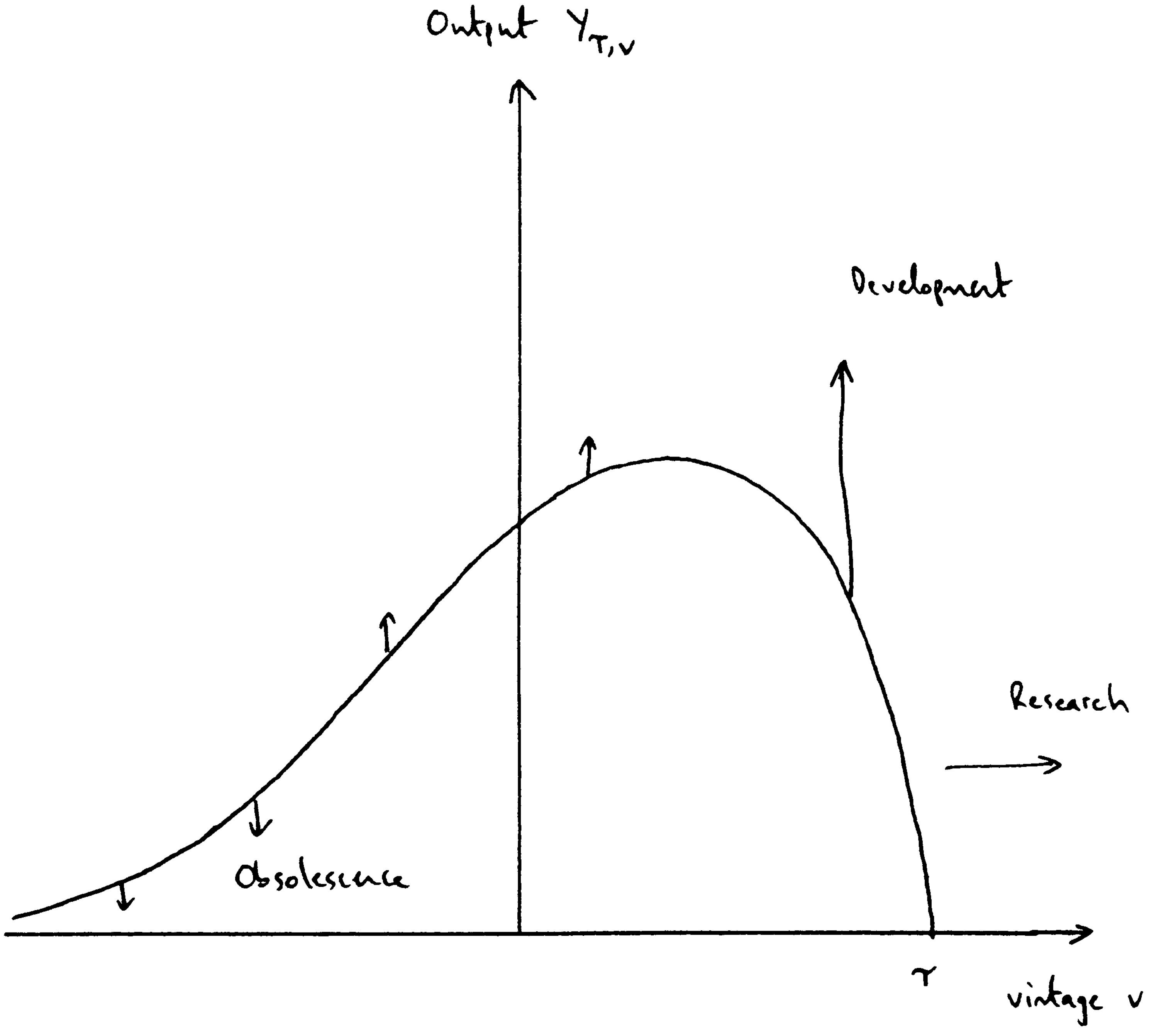
Research and Development

While unskilled labour is employed in intermediate input manufacture, skilled workers may engage in either research or development. We denote the mass of skilled labour employed in research at time τ by H_τ^r and the corresponding mass employed in development by $H_\tau^d = H - H_\tau^r$.

Each researcher is assumed to discover a fundamental innovation with Poisson probability λ^r, and hence the flow of new fundamental lines at time τ equals $\lambda^r.H_\tau^r$. On each existing line, blueprints for new intermediate inputs are developed by skilled workers who have chosen to develop a product line of that vintage, with the assistance of the researcher who discovered the line. Initially, we assume that once a skilled worker has chosen to develop a product line, she cannot do anything else until she is exogenously upgraded, which occurs at a fixed Poisson rate σ. Furthermore, we assume that, once she is upgraded, she chooses either to go into research or to develop a line of the most recent vintage.[5]

---

[5] In a later Section of the paper, Aghion and Howitt (1996a) relax this assumption and allow skilled workers to move instantaneously and costlessly between research and the development of each line.



<u>Figure 5</u>: The evolution of output on lines of different vintages v at time τ.

We denote the flow of skilled labour entering the development of lines of the most recent vintage at time τ by h^d_τ. If h^d_τ skilled workers enter the development of lines of the most recent vintage, then each line will receive $\eta_\tau = \frac{h^d_\tau}{\lambda^r H^r_\tau}$ developers. Blueprints for new inputs or secondary innovations are assumed to arrive to each developer at a Poisson arrival rate λ^d_τ. Aghion and Howitt (1996a) assume that $\lambda^d_\tau = \lambda^d . (\eta_\tau)^{-\mu}$ $(0 < \mu < 1)$, so that the arrival rate of secondary innovations depends upon the number of skilled workers that initially choose to develop a line. At time τ, the number of developers still working on lines of vintage $v \leq \tau$ will be $h^d_v . e^{-\sigma(\tau - v)}$, and the corresponding flow of new production blueprints on those lines will be,

$$\dot{S}_{\tau,v} = \lambda^d_v . h^d_v . e^{-\sigma(\tau - v)}, \tag{4.13}$$

Under the assumptions above, the aggregate flow of skilled labour devoted to development evolves according to,

$$\dot{H}^d_\tau = h^d_\tau - \sigma . H^d_\tau = h^d_\tau - \sigma . (H - H^r_\tau),$$

In steady-state, $\dot{H}^d_\tau = 0$, and,

$$h^d = \sigma . (H - H^r), \tag{4.14}$$

As argued above, both *fundamental* and *secondary* innovation may contribute to the growth of general knowledge. Aghion and Howitt (1996a) assume that the log of A_τ is proportional to a weighted average of the stock of fundamental and secondary innovations, with weights β and $(1-\beta)$ respectively.[6] Hence, the stock of general knowledge evolves according to,

$$\frac{\dot{A}_\tau}{A_\tau} = \psi\left(\beta, \lambda^r, H^r_\tau, \lambda^d, H^d_\tau\right), \tag{4.15}$$

where in steady-state $H^r_\tau = H^r$ and $H^d_\tau = H - H^r$. A special, benchmark case is where $\beta = 1$ and the stock of general knowledge is proportional to the existing stock of fundamental innovations,

$$\frac{\dot{A}_\tau}{A_\tau} = \lambda^r.H^r_\tau, \tag{4.16}$$

Steady-state Equilibrium

In steady-state equilibrium, final goods output, consumption and the wage rate grow at the same constant rate g as the stock of general knowledge. The steady-state equilibrium allocation of skilled labour to research H^r is defined by two sets of relationships. On the one hand, there is the *growth equation* or the equation of motion for A_τ (given by either (4.15) or (4.16)). On the other hand, in an equilibrium characterised by positive levels of both research and development, we require that a *no-arbitrage* condition equate the present discounted returns from the two activities.

---

[6] These weights may be derived endogenously from a model of knowledge spillovers following Caballero and Jaffe (1993).

For simplicity, we restrict attention to the benchmark case where the stock of general knowledge is proportional to the existing stock of fundamental innovations. In this case, the growth equation (G) is simply,

$$\textbf{(G)} \qquad g = \lambda^r.H^r, \tag{4.17}$$

We denote the expected present discounted value of the income that a researcher will receive until his alternative choice as a developer is upgraded to a new line by $V_\tau^r = V^r.e^{g\tau}$. The corresponding value of the income the researcher would have received in development over the same period is denoted by $V_\tau^d = V^d.e^{g\tau}$, and in steady-state equilibrium we require,

$$V^r = V^d, \tag{4.18}$$

When developers first begin work on a line, it is agreed that a certain fraction κ of the profits from developing a line will go to the researcher, with $(1-\kappa)$ going to developers. At each point in time, there are $\lambda^r.H^r$ researchers competing for developers using κ as their strategic value. This competition defines a unique equilibrium value of κ equal to μ. Hence, in equilibrium , the rents from a developing each product line are shared in the constant proportions μ and $(1-\mu)$.

We denote the capitalised value of rents generated by the intermediate inputs on each product line opened at time τ by $W_\tau = W.e^{g\tau}$. Upgrading occurs at Poisson rate σ, and hence, from the above, the Bellman equation defining the steady-state value of V^r is,

$$r.V^r = \lambda^r.\mu.W - \sigma.V^r + g.V^r, \tag{4.19}$$

Each developer receives a fraction $1/\eta = \lambda^r H^r / h^d$ of $(1-\mu).W$, and hence the steady-state value of V^d is simply,

$$V^d = \frac{\lambda^r.H^r}{h^d}.(1-\mu).W, \tag{4.20}$$

Using the steady-state condition (4.14), together with (4.19) and (4.20), the no-arbitrage condition (A) equating the returns to research and development is given by,

$$\textbf{(A)} \qquad r + \sigma - g = \frac{\mu}{1-\mu}.\sigma.\frac{H - H^r}{H^r}, \tag{4.21}$$

The steady-state equilibrium values of g and H^r are jointly determined by the no-arbitrage equation (A) and the growth equation (G) above. Equilibrium may be illustrated diagrammatically, and in Figure 6 we plot (A) and (G) in g, H^r space. In the benchmark case (4.16), the economy's growth is determined by the equilibrium allocation of skilled labour to *research.* Comparative statics may be established directly from Figure 6. The growth rate g and equilibrium research employment H^r are monotonically increasing in the productivity of research λ^r, the supply of skilled labour H and the share of rents received by researchers μ. Both are monotonically decreasing in the rate of time preference ρ.

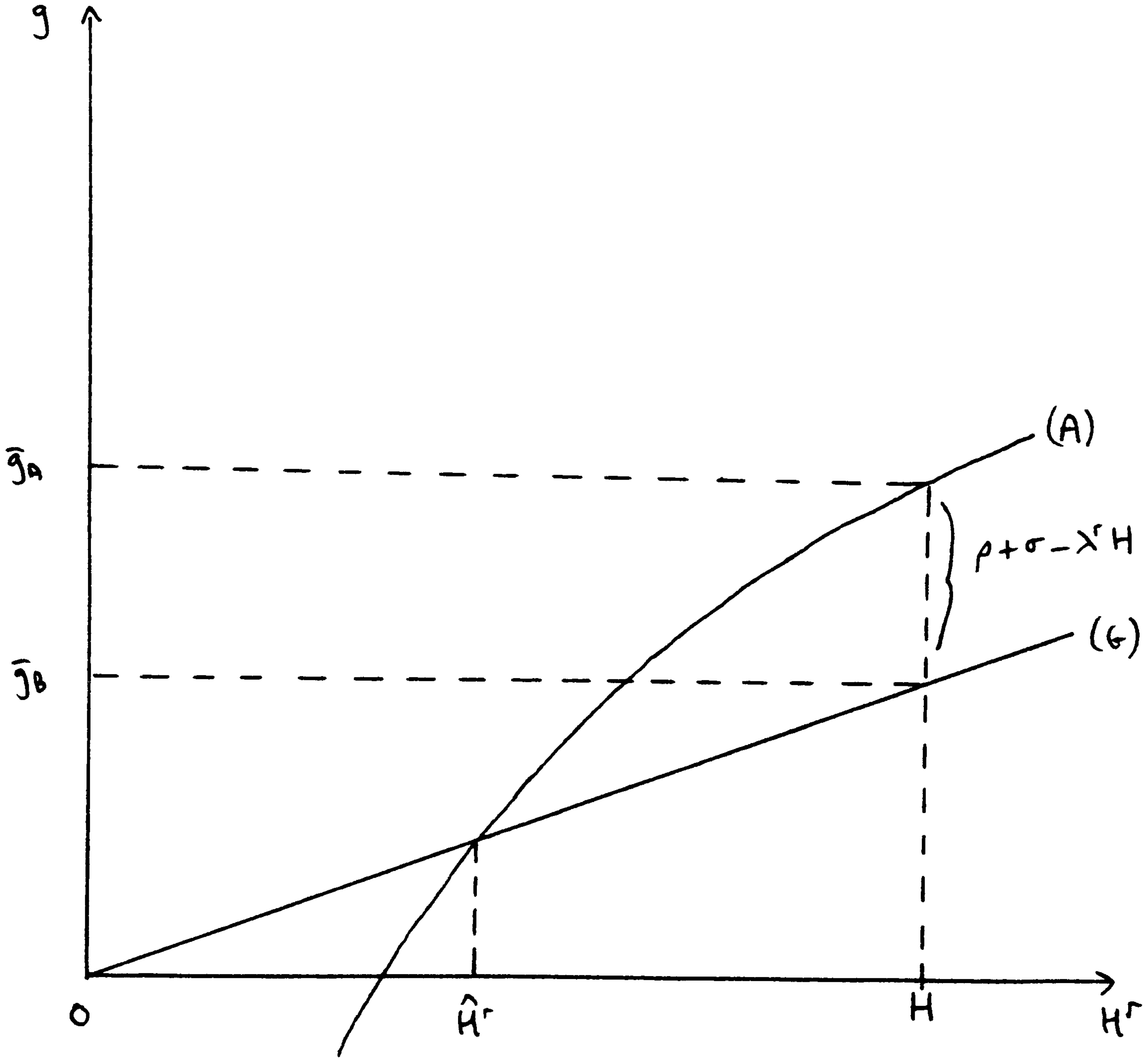


Figure 6: Steady-state equilibrium in the benchmark case (stock of general knowledge proportional to existing stock) of fundamental innovations

Existence requires $\bar{g}_A > \bar{g}_B$

In Aghion and Howitt (1996a), skilled labour can be only employed in either research or development. Hence, there is a sense in which the total amount of innovation (fundamental and secondary is fixed). Nonetheless, from the analysis above, the economy's growth rate responds to many parameter changes in the same way as in the Schumpeterian models surveyed in Chapter 2. The growth rate g and equilibrium research employment H^r are increasing the probability of upgrade σ, which determines the flow of skilled labour available for new lines. σ may be thought of as parameterising the adaptability of an economy. Hence, Aghion and Howitt (1996a) argue that this result provides some support for Lucas (1993)'s claims that the rapid growth of the Newly Industrialising Countries (NICs) may be due in part to their ability to reallocate skilled labour between sectors.

Interestingly, the productivity of development λ^d has no effect upon the steady-state equilibrium growth rate and allocation of skilled labour to research. An increase in λ^d raises the capitalised value W of the rents generated by intermediate inputs on a line. However, in equilibrium, the rents generated from the development of each line are shared in the constant proportions μ and $(1-\mu)$ between researchers and developers respectively. Hence, changes in λ^d do not affect the relative incentive to engage in either research or development.

4.4 Conclusion

This Chapter has been concerned with the idea that the realisation of the full productive potential of an innovation is dependent upon a process of further productivity improvement.

Considerable evidence existing that learning by doing is extremely important in the realisation of productive potential. The Chapter began with a review of the Young (1991) model of endogenous growth through bounded learning by doing. This was followed by an exposition of Young (1993a), in which a Schumpeterian model of the discovery of new technologies is combined with a specification where the productivity potential of these technologies is gradually realised through bounded learning by doing.

The central point is that one may draw a distinction between different dimensions of innovation. Following Aghion and Howitt (1996a), we distinguish fundamental innovations or major breakthroughs, such as the steam engine, from the secondary innovations that realise the opportunities latent in each breakthrough. Thus, in the case of the steam engine, the boring mill and the "sun and planet" gearing system constitute example of secondary innovations. In Aghion and Howitt (1996a), both fundamental and secondary innovation are the result of purposive investments, and it is possible to consider the determinants of the equilibrium allocation of resources between the two activities. In the next Chapter, we apply the distinction between the two forms of innovation to a question raised in the economic history literature: namely, whether there is in some sense a "penalty" to being a pioneer of a technology.

Chapter 5

Is There a Penalty to Being a Pioneer ?

5.1 Introduction,[1]

> "The British have not sinned against the canons of technology. It is only that they are paying the penalty for having been thrown into the lead."[2]

As observed by a number of economic historians, the late-nineteenth and early-twentieth centuries were, for Britain, an era of relative decline. In 1870, British GDP per capita was second in the world, exceeded only by the sparsely populated and resource rich Australia.[3] Between 1870 and 1950, the British economy grew at an average annual rate of 1.01 per cent. However, by 1950, British GDP per capita was seventh in the world, and the United States had assumed the role of the world leader. In more recent years, authors have begun to debate the relative decline of the United States, as, between 1973 and 1992, Japanese GDP per capita

---

[1] This Chapter is based upon a paper accepted for the Royal Economic Society Conference 1996, "Is There a Penalty to Being a Pioneer ?", *Nuffield College Discussion Paper, No.109.*

[2] Veblen (1915), p. 128, cited in Kindleberger (1961).

[3] All figures in this first paragraph are derived from Maddison (1995) and Crafts (1996).

rose from 66 per cent to 90 per cent of the U.S. level.

Relative decline may be explained in a number of ways. Firstly, one might propose an explanation based upon structural parameters: a number of factors may have inhibited growth in late-nineteenth and early-twentieth century Britain. For example, in terms of the one-dimensional Schumpeterian models of Chapters 2 and 3, Britain may have been characterised by a high discount rate or deficiencies in education and training. Secondly, relative decline may be explained in terms of the transition to steady-state. Thus, the neoclassical Solow-Swan (1956) model of economic growth implies that, controlling for the determinants of the steady-state level of income, an economy's growth rate is negatively correlated with its initial level of income.[4] In a similar way, models of technology transfer, such as Parente and Prescott (1994), imply that, *ceteris paribus*, an economy's growth rate should be positively correlated with distance from the technological frontier.

In this Chapter, we will be concerned with an alternative explanation for relative decline, based upon the idea that there is in some a sense a "penalty" to being a pioneer. Within the context of a Schumpeterian model of endogenous growth, we consider whether an economy that innovates first (a *pioneer* or *early-starter*) experiences disadvantages which act to systematically reduce its rate of economic growth relative to an economy innovating later (a *late-starter*). In certain circumstances, it is possible for a pioneer to become *locked-into* an existing technology.

---

[4] This Proposition has been the starting point for a large proportion of the existing literature on income convergence. This literature is discussed in a later footnote and is surveyed in Chapter 7.

However, it is by no means necessary that there exists a penalty to a being a pioneer, and we also address the alternative hypothesis that there are various advantages to an early-start.

The source for both the advantages and disadvantages of an early-start lies in Aghion and Howitt's (1996a) distinction between fundamental and secondary innovation introduced in the previous Chapter. For the present, we consider whether or not there is a penalty to being a pioneer within a closed economy model of endogenous growth. That is, we consider the comparative static implications of an early start for the incentive to innovate, the rate of growth and levels of economic welfare. In Chapter 7, we relate the present analysis to the case of an open economy. Interestingly, if there is a "penalty" to being a pioneer, it provides an alternative rationalisation for empirical findings of income *convergence* (the "poor" catching up with the "rich") to those suggested in the existing literature.[5]

Section 2 introduces the idea that there might be a "penalty" to being a pioneer and surveys the existing literature. In Section 3, we discuss the distinction between fundamental and secondary innovation and set out the basic framework for analysis. Section 4 considers the determinants of the equilibrium level of employment in research and production. Section 5 then extends the analysis to introduce knowledge spillovers into the research sector. Section 6 shows that, under certain circumstances, technological lock-in may occur. Section 7 solves

---

[5] The precise definition of income convergence will be discussed in greater detail in Chapter 7. Barro and Sala-í-Martin (1991, 1992) provide evidence of so-called absolute β-convergence for U.S. states, while Mankiw, Romer and Weil (1992) obtain estimates of conditional β-convergence in the Summer and Heston (1988) cross-country data set. This notion of convergence has been forcibly criticised by Quah (1993a), (1993b), (1996a), (1996b) and (1996c). Using the Summers and Heston cross-country data set, Quah (1993a), (1993b) and (1996a) finds evidence for the polarisation of incomes into "convergence clubs."

for the economy's average rate of growth, while Section 8 is concerned the welfare implications of pioneer status. In Sections 9 and 10, we consider two extensions to the basic analysis. Section 9 introduces bounded learning by doing, while Section 10 analyses the case of temporary technological lock-in. Finally, Section 11 concludes.

5.2 Advantages and Disadvantages of an Early Start

The idea that there may be in some sense a "penalty" to being a pioneer has a long parentage in the economic history literature. The idea dates back at least to Veblen (1915), and important contributions include Frankel (1955) and Kindleberger (1961). In the Schumpeterian endogenous growth model, with which this Chapter will be concerned, pioneer status is associated with being the first economy to innovate. We consider four forms that the "penalty" to being a pioneer might take. Firstly, an early-starter may experience a reduced incentive to invest in Research and Development (R & D) directed at the discovery of the next technology.

Secondly, the return to continuing to employ the existing technology rather than investing in R & D may be so large in a pioneering economy that it becomes *locked-into* an existing technology. Thirdly, either a reduced incentive to invest in R & D or technological lock-in may translate into a lower rate of economic growth in a pioneer than in an early-starter. It is this reduction in the rate of growth that is necessary if pioneer status is to explain relative economic decline and income convergence. Finally, pioneer status may reduce a representative agent's economic welfare relative to the level enjoyed in a late-starter.

A number of *institutional* explanations exist for a penalty to being a pioneer so defined. Olson (1982) argues that, the longer the uninterrupted period of economic growth an economy has enjoyed, the more heavily entrenched special interest groups will be in that economy. These special interest groups are assumed to slow an economy's rate of growth, by limiting its capacity to adopt new technologies and to reallocate resources to new sectors. This Chapter proposes an alternative *technological* explanation, rooted in Aghion and Howitt's (1996a) distinction between fundamental and secondary innovation. We consider the existence of a penalty to pioneer status within a general equilibrium model of endogenous growth, consistent with individual optimisation by representative agents.

The distinguishing feature of a pioneer of one fundamental technology is that she is characterised by a larger stock of secondary knowledge associated with that technology than an otherwise identical latestarter. This stock of secondary knowledge may constitute an *advantage* of an early start if there are substantial *knowledge spillovers* in either *production* or *research.* However, the same knowledge stock will be a *disadvantage* if secondary knowledge is specific to a fundamental technology and is rendered *obsolete* by fundamental innovation. If the extent of this obsolescence is sufficiently large, then a penalty to being a pioneer may emerge in all four senses above.

Although the question of the penalty to being a pioneer has been a recurrent one in economic history, it has received relatively little attention in the economics literature.[6] Two recent papers

---

[6] An industrial organisation literature exists that is concerned with whether or not there is a first-mover

have addressed related issues. Firstly, Brezis *et al.* (1993) present a model of trade and growth in which a latestarter's income per capita may overtake or "leapfrog" that of a pioneer. A distinction is drawn between major breakthroughs and incremental technological progress, and their analysis receives further attention in Chapter 7. In Brezis *et al.*, the arrival of what we term fundamental innovations is *exogenous*, and technological lock-in is the sole form that the penalty to being a pioneer might take. There are no spillovers of secondary knowledge across fundamental technologies, and hence a pioneer can never experience a higher rate of growth (an advantage to an early-start). Furthermore, no welfare analysis is undertaken.

Secondly, Jovanovic and Nyarko (1994) consider a model of Bayesian learning, where a single agent decides at fixed intervals of time whether or not to adopt a new technology and (in one section) the size of the technological jump. Within this framework, an agent that adopts a technology early may be characterised by either an increased or a reduced incentive to adopt the next technology depending upon the correlation of an unknown technology-specific parameter across technologies. In contrast, the present analysis considers the question of the penalty to being a pioneer within a general equilibrium framework, in which the discovery of new technologies requires purposive research. As a result, additional effects emerge, and it is possible to analyse the implications of pioneer status for an economy's rate of growth and

---

advantage in the choice of technology at the firm level (see for example Beath, Katsoulacos and Ulph (1989), Fudenberg *et al.* (1983), Harris and Vickers (1985), and Tirole (1988), Chapter 10). In contrast, the present analysis is concerned with the existence of the penalty to being a pioneer at an economy-wide level, in the context of a general equilibrium model of endogenous growth.

economic welfare. In particular, we are able to address the question of whether the destruction of secondary knowledge, through an event such as a war, can alleviate the penalty to being a pioneer, accelerate growth and increase economic welfare.

5.3 The Model

We consider an economy populated by a sequence of non-overlapping generations, indexed by t. Each generation consists of a continuum of consumer-producers of mass H. Agents live for two periods and then die. Time is discrete and is indexed by τ. We choose units for time such that each period lasts for one unit of time.

The economy is composed of three sectors: final goods, intermediate inputs and research. Final goods output is produced with intermediate inputs, whose quality depends upon the economy's stock of *fundamental* and *secondary* knowledge. Intermediate inputs are produced with skilled labour. Skilled labour may also be employed in research directed at the discovery of new fundamental technologies, while secondary knowledge accumulates as a result of learning by doing.

5.3.1 Consumers

Consumer preferences are intertemporally additive separable, with linear per period utility defined over consumption c of an homogeneous final good,

$$U_t(c_{1,t}, c_{2,t}) = c_{1,t} + \left(\frac{1}{1+\rho}\right) c_{2,t}, \tag{5.1}$$

where ρ denotes the subjective rate of time preference. Consumers are thus risk neutral, and the interest rate r_t equals ρ.

Each consumer is endowed with one unit of skilled labour, which is supplied inelastically with zero disutility. Each consumer must decide whether to work in the production sector or to engage in research to develop the next fundamental technology. Since both production and research typically involve the acquisition of specialised skills, we assume that this decision is irreversible and must be made at birth.

5.3.2 Production

Final Goods Production

Final goods output Y is produced with intermediate inputs x according to a Cobb-Douglas technology, and the period j flow of final goods output is thus given by,

$$Y_{j,t} = F^{v}_{j,t} S_{j,t} . x^{\alpha}_{t}, \qquad 0 < \alpha < 1, \qquad v > 0, \qquad j = 1, 2, \tag{5.2}$$

The quality or productivity of intermediate inputs is assumed to depend upon each period's stock of fundamental and secondary knowledge F and S respectively. Fundamental knowledge corresponds to information concerning basic technological principles such as steam power, the internal combustion engine or nuclear power, and each fundamental innovation constitutes a "major breakthrough." In contrast, secondary knowledge refers to the sequence of minor improvements that have been made to each fundamental technology. Thus, in the case of the internal combustion engine, examples of secondary innovations include the fuel injection system and the turbocharger.

Secondary knowledge is specific to the fundamental technology under which it was acquired. In terms of the example used in Chapter 4, the boring mill and the "sun and planet" gearing system were developed for steam power, and have been of limited use in the development of the internal combustion engine. Nonetheless, undoubtedly some of the incremental improvements to the steam engine were of relevance to the internal combustion engine (e.g. piston technology), and we will allow secondary knowledge to spillover across fundamental technologies. Each fundamental innovation raises the stock of fundamental knowledge by a constant proportion $\gamma > 1$, and the structure of knowledge is thus as illustrated in Figure 1.

Substantial evidence exists that spillovers of knowledge across international borders are far from perfect. Hence, we assume that the stocks of fundamental and secondary knowledge are specific to each economy.[7] Fundamental and secondary knowledge spillover across generations, and at the beginning of period 1, individual agents inherit the economy-wide stocks of knowledge

---

[7] Coe and Helpman (1993) provide evidence that R & D spillovers are significantly smaller across international borders than within them. Islam (1995) and Caselli, Esquivel and Lefort (1995) provide empirical evidence of substantial differences in total factor productivity (TFP) across economies. For example, Islam (1995) estimates that TFP in the United States is over 5 times that in the Philippines and 27 times that in Somalia. The analysis may be generalised to allow spillovers of knowledge across economies, as long as these spillovers are incomplete.

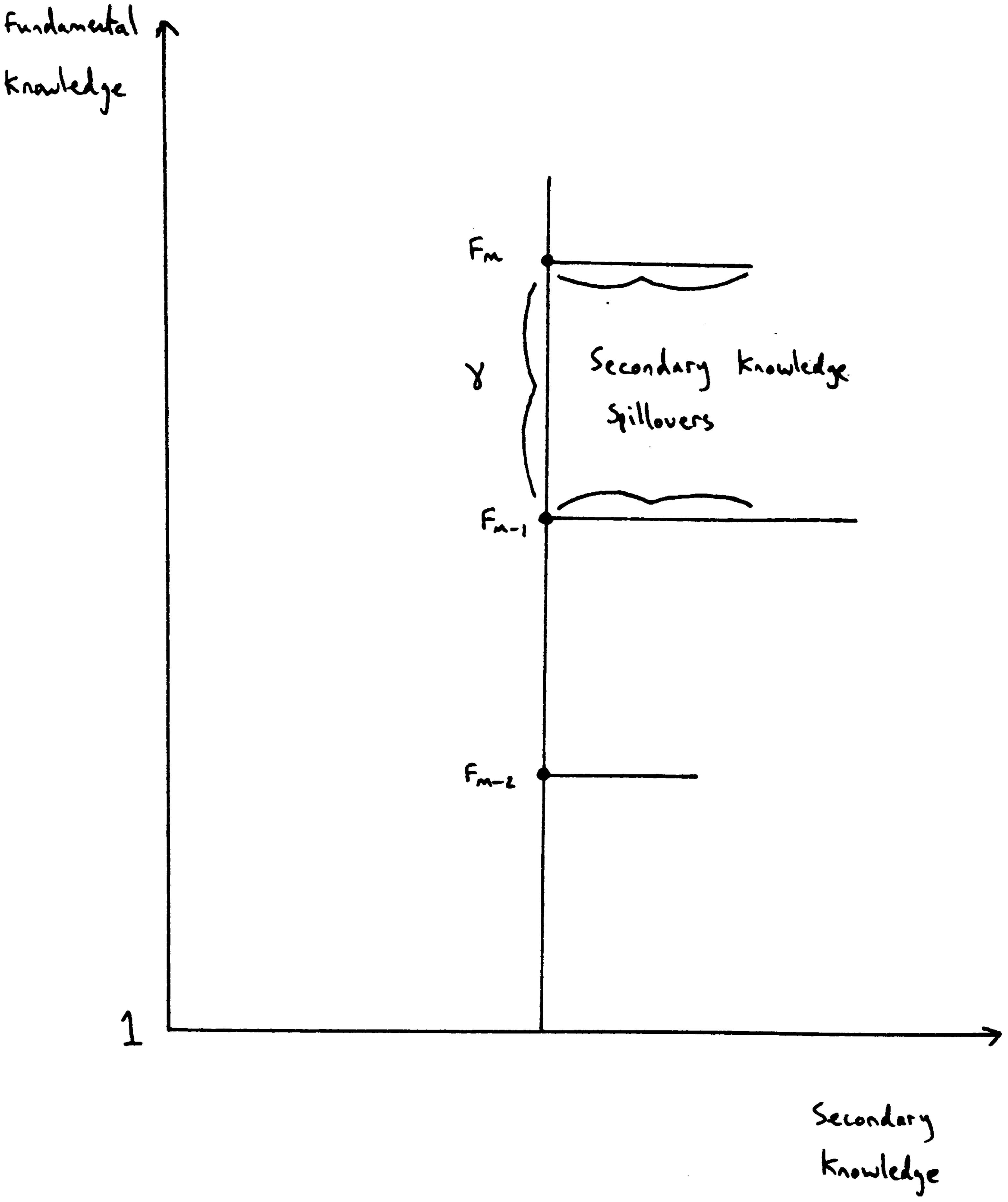


Figure 1: Fundamental and Secondary Innovation.

$F_{1,t}$ and $S_{1,t}$ from the preceding generation.[8] Fundamental and secondary knowledge combine in an index $\Theta \equiv F^{\nu} S$ to determine the quality or productivity of intermediate inputs. For all $\nu > 0$, fundamental and secondary knowledge are complementary in the production.[9]

Final goods production is assumed to occur under conditions of perfect competition. We choose final goods output for numeraire, and hence $p(Y_{j,t}) = 1$ for all j, t.

Intermediate Input Production

At the beginning of period 1, each representative agent must make an irreversible decision whether to work in the production sector (manufacturing intermediate inputs) or whether to engage in fundamental research. Intermediate inputs are produced from skilled labour according to the following constant returns to scale technology,

$$x_t = h_t, \tag{5.3}$$

where $h_t = H - n_t$ denotes the number of individuals in generation t who choose to enter the production sector, and n_t the corresponding number who choose to do fundamental research. As a result of the technological spillover across generations, in period 1 all agents have access to the same stocks of fundamental and secondary knowledge, and intermediate input production occurs under conditions of perfect competition.

---

[8] The analysis may be generalised to allow imperfect knowledge spillovers across generations. For example, is is straightforward to introduce an exogenous rate of depreciation of knowledge across generations χ, such that $0 < \chi < 1$. However, no particular insight is added.

[9] Complementary in the sense that the marginal product of one is increasing in the quantity of the other.

5.3.3 Knowledge Accumulation

Fundamental Research

The discovery of "major breakthroughs," such as the internal combustion engine, is assumed to be the result of profit-seeking investments in Research and Development (R & D). Following Aghion and Howitt (1992), the research technology is assumed to be stochastic. Research is assumed to take one period, and all research uncertainty is realised at the end of period 1. A successful researcher receives a one-period patent on the new technology, which may be employed in intermediate input production in period 2. In this case, period 2 intermediate input production is imperfectly competitive. If research is unsuccessful, then intermediate input production in period 2 continues with the existing technology.

If $n_t \geq 0$ individuals enter the research sector in period 1, then we assume that with probability $\lambda(n_t).n_t$ *one* researcher discovers the next fundamental technology. The probability that a fundamental innovation occurs at the end of period 1 is thus,

$$\iota = \lambda(n_t).n_t, \qquad n_t \geq 0, \quad 0 < \lambda(H).H < 1, \tag{5.4}$$

For $n_t > 0$, the probability that *any one individual* discovers the next fundamental technology is simply $\frac{\iota}{n} = \lambda(\cdot)$. The function $\lambda(n_t)$ characterises the productivity of research. Research may exhibit either positive externalities or congestion, where respectively $\frac{\partial\lambda(\cdot)}{\partial n} > 0$ and $\frac{\partial\lambda(\cdot)}{\partial n} < 0$. However, we will largely be concerned with the simplest baseline case of constant returns to scale in research where $\lambda(n_t) = \lambda$.[10]

Each fundamental innovation is assumed to be $\gamma > 1$ times as productive as the preceding one. Hence, normalising the initial stock of fundamental knowledge to 1, we have,

$$F_{j,t} = \gamma^m, \tag{5.5}$$

where $m = 0, 1, ..., M$ denotes the interval starting with the m^{th} fundamental innovation and ending just before the $m + 1^{\text{st}}$, and $M_{j,t}$ denotes the most sophisticated fundamental technology available in period j of generation t.

Secondary Knowledge Accumulation

The opportunities latent in each "major breakthrough" are realised through a sequence of incremental improvements or secondary innovations. As discussed in Chapter 4, a wide range of evidence suggests that learning by doing is an extremely important source of productivity improvement for new technologies. Hence, secondary innovation is assumed to take the form of serendipitous learning by doing. If a fundamental technology is employed for two consecutive periods j and $j-1$, then the stock of secondary knowledge inherited in period j is,

---

[10] According to the specification in (5.4), there is zero probability that more than one fundamental researcher discovers the next technology in period 1. More generally, we might suppose that (in the constant returns case) the probability of any one individual innovating is λ and that, if more than one individual innovates in period 1, the patent to that innovation is allocated randomly to one of these individuals. Hence, the probability of any one individual obtaining the patent to an innovation is $\frac{1}{n_t}.[1-(1-\lambda)^{n_t}]$. For small values of λ and large values of n_t, $\frac{1}{n_t}.[1-(1-\lambda)^{n_t}] \simeq \lambda$.

$$S_{j,t} = (1+g).S_{j-1,t}, \tag{5.6}$$

where the rate at which secondary knowledge accumulates g is determined by the current flow of intermediate goods output,

$$g = \mu.x \qquad \mu \geq 0, \quad x \geq 0, \tag{5.7}$$

The specification in equations (5.6) and (5.7) implies that learning by doing is *technologically unbounded.* As argued in Chapter 4, some evidence exists that there are diminishing returns to the accumulation of production experience. Hence, Section 9 considers the case of *bounded* learning by doing. For the present, we restrict consideration to the simpler unbounded case.

The secondary knowledge accumulated under one fundamental technology may exhibit varying degrees of relevance to the next. On the one hand, some secondary innovations are likely to be specific to a given fundamental technology and will therefore be rendered obsolete by the discovery of the next. For example, the boring mill, discovered by John Wilkinson in 1776, greatly increased the power of the steam engine, but is likely to have had little impact on the productivity of the internal combustion engine. This *secondary knowledge obsolescence* is another example of the way in which growth is essentially a process of *creative destruction.* On the other hand, some secondary innovations may raise the productivity of one fundamental technology, but may only realise their true potential under subsequent fundamental technologies. Thus, the improvements in piston technology made under the steam engine may have raised the latter's productivity, but may have had an even greater impact when the internal combustion engine was discovered. This second case might be described as "*ideas arriving before their time.*"

In general, the stock of secondary knowledge relevant to a fundamental innovation m will be some function of the stock accumulated under the previous fundamental technology $m-1$, $S_m = \theta(S_{m-1})$. For simplicity, we assume that this function takes the following form,

$$S_m = \begin{cases} \theta.(S_{m-1})^{\sigma} & \text{for } \theta.(S_{m-1})^{\sigma} \geq 1 \\ & \\ 1 & \text{for } \theta.(S_{m-1})^{\sigma} < 1 \end{cases}, \qquad 0 < \theta < 1,\ \sigma > 0, \tag{5.8}$$

The stock of secondary knowledge is assumed to be bounded below by 1, which may be thought of as a minimum amount of secondary knowledge, freely available simply in virtue of a fundamental technology having been discovered in the research sector. Above this lower bound, the stock of secondary knowledge relevant to a fundamental innovation S_{m+1} is a constant elasticity function of the stock accumulated under the existing fundamental technology S_m.

The extent of the secondary knowledge that spills over from one technology to the next is determined by both σ and θ. However, it is σ which determines whether a marginal increase in the stock of secondary knowledge S_m raises the flow of final goods output produced with the existing fundamental technology m by proportionately more than that produced with the subsequent technology $m+1$. From equation (5.2), the elasticity of final goods output produced with intermediate inputs of fundamental technology m with respect to S_m is simply 1. However, from (5.2) and (5.8), the elasticity of final goods output produced with fundamental technology $m+1$ with respect to S_m is σ.

According to whether σ is less than or greater than 1, an increase in the stock of secondary knowledge accumulated under one fundamental technology raises the current flow of final goods output by more than it increases the flow of output produced under the subsequent fundamental technology. Thus, *secondary knowledge obsolescence* and *ideas arriving before their time* may be parameterised as the cases where $\sigma < 1$ and $\sigma > 1$ respectively.

Whether or not a fundamental innovation occurs depends upon the number of individuals entering the research sector. If fundamental innovations occur, they take place at the end of period 1. Hence, in any generation t, the period 2 stock of secondary knowledge is given by,

$$S_{2,t} = \begin{cases} \max[1, \theta.S_{1,t}^{\sigma}] & \text{with probability } \lambda.n_t \\ \\ (1+g).S_{1,t} & \text{with probability } (1-\lambda.n_t) \end{cases}, \tag{5.9}$$

Learning by doing occurs in period 2. Hence, the period 1 stock of secondary knowledge inherited by any generation t is simply,

$$S_{1,t} = (1+g).S_{2,t-1},$$

where $g = \mu.(H - n_t)$. We denote the number of generations since the discovery of the current state of the art fundamental technology m by $\phi \in [1, \infty)$.[11]

---

[11] Thus, $\phi = 1$ denotes the case where the preceding generation discovered technology m.

5.4 General Equilibrium

At birth, agents make an irreversible decision whether to enter the production or research sectors. In an equilibrium in which a positive quantity of resources is devoted to both intermediate input production and research, we require that individuals are indifferent between the two sectors. We begin by solving for the expected present discounted value of a lifetime spent in the production sector.

5.4.1 Intermediate Input Production

The demand for intermediate inputs is derived from the final goods production technology (5.2), and is given by,

$$p_{j,t}(x_t) = \alpha.F_{j,t}^{\nu}S_{j,t}.x_t^{\alpha-1}, \tag{5.10}$$

Period 1

In period 1, all agents have access to the same production technology. Intermediate input production occurs under conditions of perfect competition. Hence, the period 1 wage received by an individual entering the production sector is simply,

$$w_{1,t} = \alpha.F_{1,t}^{\nu}S_{1,t}.x_t^{\alpha-1}, \tag{5.11}$$

where $S_{1,t}$ denotes the stock of secondary knowledge specific to a given fundamental technology m inherited by generation t.[12]

Period 2

Prima facie, the period 2 wage in the production sector would appear to depend upon whether or not a fundamental innovation occurs at the end of period 1. If research is unsuccessful, intermediate input production remains perfectly competitive and the productivity of intermediate inputs rises as a result of serendipitous learning by doing. Hence, from (5.11) and (5.6),

$$w_{2,t} = (1+g).w_{1,t} \qquad \text{with probability } (1-\lambda.n_t), \tag{5.12}$$

If research is successful, one researcher (the entrepreneur) acquires a one-period patent for the new fundamental technology. Technologies are vertically differentiated, and in equilibrium only one fundamental technology will be employed. In order for this to be the state of the art technology, three conditions must be met. Firstly, agents in the production sector must receive at least as high a wage working for a successful researcher (the entrepreneur), as from employing the existing fundamental technology. Secondly, at the implied price of the state of the art technology, final goods producers must be indifferent between or prefer to employ the new fundamental technology rather than its predecessor. Thirdly, in equilibrium the entrepreneur must enjoy positive period 2 profits.

We begin with the first condition. Entrepreneurs are assumed to make a "take it or leave"

---

[12] In order to simplify notation, we suppress the implicit dependence of $S_{1,t}$ on m.

offer to agents in the production sector. In equilibrium, the entrepreneur proposes a wage w^p equal to their outside option w^o, which, from (5.12), is given by $w^o = (1+g).w_{1,t}$.[13] Hence, if it is profitable for the new fundamental technology to be adopted (the condition for which we will derive below), the first condition above will be met. Contrary to first appearances, the equilibrium period 2 wage is in fact independent of whether or not a fundamental innovation occurs at the end of period 1,

$$w_{2,t} = (1+g).w_{1,t} \qquad \text{with probability } \lambda.n_t, \tag{5.13}$$

Turning now to the second and third requirements above, the derived demand for intermediate inputs is given by (5.10). Hence, the equilibrium period 2 price of a newly discovered fundamental technology is,

$$p_{2,t}(x_t) = \alpha.\gamma^{\nu}.F^{\nu}_{1,t}.\theta.S^{\sigma}_{1,t}x_t^{\alpha-1} = \gamma^{\nu}.\theta.S^{\sigma-1}_{1,t}.w_{1t}, \tag{5.14}$$

Final goods producers will employ the state of the art fundamental technology if and only if the implied unit costs of production are the same as or strictly less than those with the preceding technology. From the Cobb-Douglas cost function, this requires fundamental innovations to be

---

[13] The analysis is easily extended to the case of Nash Bargaining between the entrepreneur and workers in the production sector. In this case, the entrepreneur and workers solve,

$$\max_{w^p} \left(p(x).x - w^p.x\right)^{1-\beta} . \left(w^p - w^o\right)^{\beta},$$

The analysis remains essentially the same, the expressions for the expected present discounted value of a lifetime in the production and research sectors merely become slightly more complicated.

productivity enhancing. That is,[14]

$$\gamma^{\nu}.\theta.S_{1,t}^{\sigma-1} > 1+g, \tag{5.15}$$

Initially, we restrict consideration to equilibria where this condition is satisfied. Section 8 relaxes this assumption and considers the case of technological lock-in. Given the constant returns to scale technology for producing intermediate inputs, the equilibrium period 2 flow of profits from successful research equals $\pi_{2,t} = p_{2,t}(x_t).x_t - w_{2,t}.x_t$. Substituting for $p_{2,t}(\cdot)$ using (5.14) and $w_{2,t}$ using (5.13), we obtain,

$$\pi_{2,t} = \left[\gamma^{\nu}.\theta.S_{1,t}^{\sigma-1} - (1+g)\right].w_{1,t}.x_t, \tag{5.16}$$

For all parameter values for which inequality (5.15) is satisfied, the equilibrium period 2 flow of profits from successful research must be strictly positive. Under the assumption that inequality (5.15) is satisfied, all three conditions above will be met and the newly discovered (state of the art) fundamental technology will be employed in final goods production.

From (5.12) and (5.13), the equilibrium expected present discounted value of lifetime in the production sector is simply,

---

[14] For the fundamental technology to be employed by final goods producers we require $c_{2m} < c_{2m-1}$, that is,

$$\gamma^{-\nu}F_{1,t}^{-\nu}\theta^{-1}S_{1,t}^{-\sigma}.\left[\gamma^{\nu}\theta S_{1,t}^{\sigma-1}w_{1,t}\right]^{\alpha}.\alpha^{-\alpha}(1-\alpha)^{\alpha-1} \leq \frac{F_{1,t}^{-\nu}S_{1,t}^{-1}(1+g)^{-1}.}{[(1+g).w_{1,t}]^{\alpha}.\alpha^{-\alpha}(1-\alpha)^{\alpha-1}},$$

$$V_{x,t} = \left(1 + \frac{1+g}{1+\rho}\right).w_{1,t}, \tag{5.17}$$

5.4.2 Research

If individuals enter the research sector, they receive no return in period 1. However, with probability λ, they obtain a one-period patent entitling them to the flow of profits from successful research. The latter is simply given by equation (5.16),

$$\pi_{2,t} = \left[\gamma^{\nu}.\theta.S_{1,t}^{\sigma-1} - (1+g)\right].w_{1,t}.x_t,$$

where (5.3) and labour market clearing imply $x_t = H - n_t$. Hence, the expected present discounted value of a lifetime in the research sector is simply,

$$V_{r,t} = \left(\frac{\lambda}{1+\rho}\right).\left[\gamma^{\nu}.\theta.S_{1,t}^{\sigma-1} - (1+g)\right].w_{1,t}\left[H - n_t\right], \tag{5.18}$$

where, by assumption, $\gamma^{\nu}.\theta.S_{1,t}^{\sigma-1} > 1+g$.

5.4.3 Equilibrium

In an equilibrium with positive levels of intermediate input production and research, we require,

$$V_{x,t} = V_{r,t},$$

$$\Leftrightarrow \quad \underbrace{(1+\rho)+(1+g)}_{MC(n_t)}=\underbrace{\lambda.\left[\gamma^{\nu}.\theta.S_{1,t}^{\sigma-1}-(1+g)\right].(H-n_t),}_{MB(n_t)} \tag{5.19}$$

$$\text{where} \qquad g=\mu.(H-n_t),$$

where the left-hand side of (5.19) denotes the marginal cost of entering the research sector $MC(n_t)$ and the right-hand side the marginal benefit $MB(n_t)$. Equilibrium research employment is determined by the marginal benefit and marginal cost of entering research.

Lemma 1 *There exists a critical value for research employment* $n_t^c < H$ *such that:* (i) *for all* $n_t < n_t^c$, $MB(n_t)$ *is monotonically increasing in* n_t, (ii) $\partial MB(n_t)/\partial n_t|_{n_t^c} = 0$, *and* (iii) *for all* n_t *such that* $n_t^c < n_t \leq H$, $MB(n_t)$ *is monotonically decreasing in* n_t.

Proof. See Appendix

An increase in the flow of skilled labour employed in research n_t reduces the corresponding flow of skilled labour employed in the intermediate input sector $h_t = H - n_t$. From equation (5.19), this means that the marginal cost of research $MC(n_t)$ is monotonically *decreasing* in n_t. The lower intermediate input employment, the smaller the rate of learning by doing g and hence the smaller the period 2 wage $w_{2,t}$. It also implies, from equation (5.19) and lemma 1, that effect of an increase in n_t on the marginal benefit of research $MB(n_t)$ is *ambiguous*.

On the one hand, the *direct* effect of lower intermediate input employment is to reduce the period 2 profits from successful research (5.16) for a given value of g. On the other hand, the *indirect* effect of lower intermediate input employment is to reduce the rate of learning by doing g, thereby decreasing production workers' outside option and the period 2 wage $w_{2,t}$. The first, direct effect *reduces* the marginal benefit of research $MB(n_t)$, while the second, indirect effect *increases* it.

Substituting for g in equation (5.19), it is clear that the marginal benefit of research $MB(n_t)$ is essentially a quadratic function of $(H - n_t)$. Thus, as stated in Lemma 1, there is critical value of research employment n_t^c such that $MB(n_t)$ is monotonically increasing in research employment for all values of $n_t < n_t^c$ and monotonically decreasing in research employment for all values of $n_t > n_t^c$. The expression for n_t^c is given in the proof of Lemma 1 and depends crucially upon the learning by doing parameter μ. As μ becomes small, the *indirect* above vanishes and the marginal benefit of research $MB(n_t)$ becomes monotonically *decreasing* in n_t.[15]

For large enough values of μ, the marginal benefit of research is affected by both the direct and indirect effects above, and takes the inverted U-shape illustrated in Figure 2. As a result, multiple equilibria are possible. As shown in Figure 2, one corner equilibrium ($n_t' = 0$) and two interior equilibria (n_t'' and n_t''') exist. If research employment is expected to be low, the

---

[15] From the proof of Lemma 1, n_t^c need not be positive, in which case $MB(n_t)$ is decreasing in n_t for all $n_t \in [0, H]$.

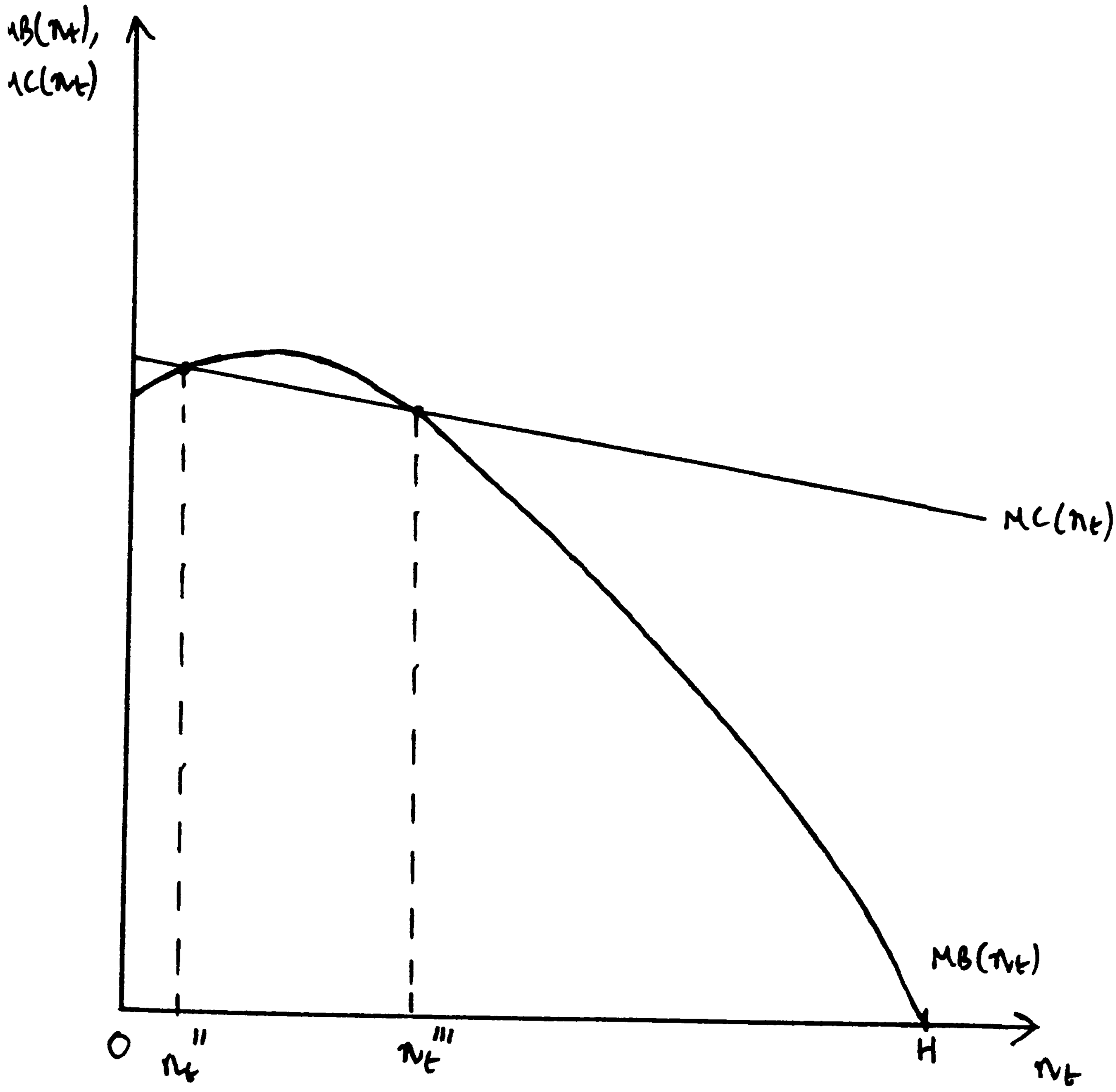


FIGURE 2: Multiple Equilibria may exist.

$$MB(n_t) = \lambda . \gamma^v . \theta . S_{1t}^{\sigma-1} . (H - n_t) - x . (H - n_t) - \mu . \lambda . (H - n_t)^2 ,$$

marginal cost of research is high and marginal benefit low. Equilibrium research employment is small, and is given by $n'_t = 0$. Alternatively, if research employment is expected to be high, the marginal cost of research is low and the marginal benefit high. In this case, equilibrium research employment is increased and is given by n'''_t. An intermediate, unstable equilibrium n''_t also exists.

Multiple equilibria arise from the interdependence between fundamental and secondary innovation. The rate of learning by doing $g = \mu.(H - n_t)$ affects both the marginal cost and marginal benefit of fundamental research, and depends upon research employment itself. Which of the multiple equilibria is selected depends entirely upon agents' expectations. Hence, as in Chapter 3, there may be a role for government policy in co-ordinating expectations on the Pareto dominant equilibrium. However, the existence of multiple equilibria does depend upon the learning parameter μ and hence the *indirect* (learning by doing) effect being large.

Throughout much of the following, we will be concerned with the case where the equilibrium allocation of resources between research and production is unique. However, the comparative statics are easily repeated for the case of multiple equilibria.

Assumption 1 $\lambda H. \left[\gamma^{\nu}.\theta.S_{1,t}^{\sigma-1} - 1\right] - \mu H.(1 + \lambda H) > 2 + \rho$

Proposition 1 *Under assumption 1, a unique interior equilibrium allocation of skilled labour between research and production* $[\hat{n}_t, (H - \hat{n}_t)]$ *exists.*

Proof. See Appendix

Assumption 1 simply requires that the marginal benefit of research exceed the marginal cost evaluated at $n_t = 0$.[16] Under this assumption, a unique interior equilibrium exists and is illustrated in Figure 3. From equation (5.19), equilibrium research employment is an implicit function $\psi(\cdot)$ of the following parameters,

$$\hat{n}_t = \psi\left(S_{1,t}, \gamma, \theta, \nu, \sigma, \mu, H, \lambda, \rho\right),$$

Comparative statics for equilibrium research employment are easily established from equation (5.19) and Figure 3.

Proposition 2 *The equilibrium allocation of skilled labour to research $\hat{n}_t$ [the equilibrium allocation of skilled labour to the production sector $(H - \hat{n}_t)$] is monotonically* increasing *[*decreasing*] :*

(i) *The larger the size of fundamental innovations γ,* (ii) *The greater the elasticity of final goods output with respect to fundamental knowledge ν,* (iii) *The higher the productivity of research λ,* (iv) *The lower the subjective rate of time preference ρ,* (v) *The larger the knowledge spillover parameter θ,* (vi) *The smaller the learning by doing parameter μ.*

Proof. See Appendix 1.

Increases in both the size of fundamental innovations γ and the elasticity ν raise the contribution of each fundamental discovery to final goods output. As a result, the derived demand for

---

[16] This assumption will be relaxed in Section 8, where we consider the phenomenon of technological lock-in.

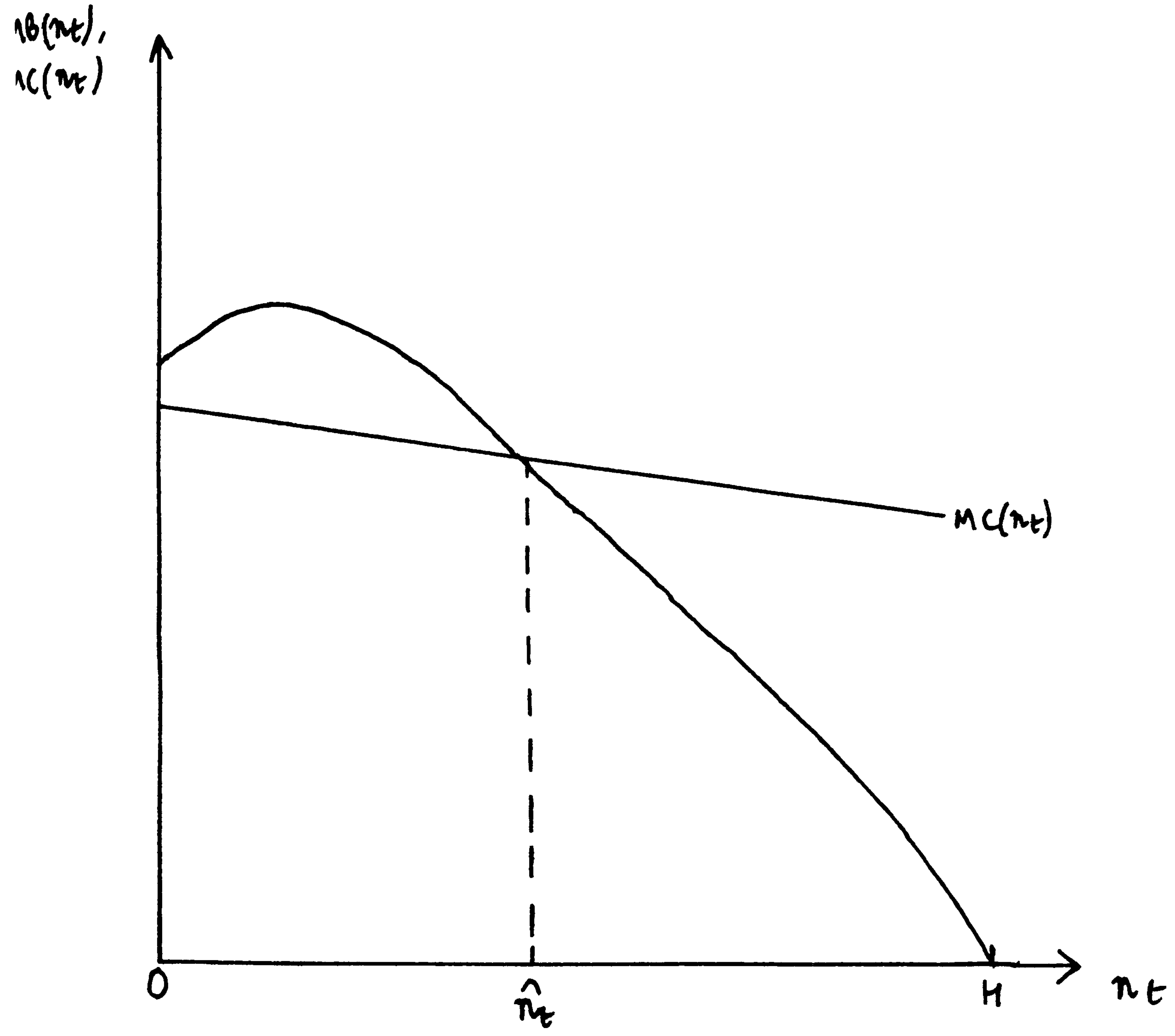


FIGURE 3: Under the assumption $\lambda(\gamma^{\nu}\theta s_{1t}^{\sigma-1}-1)H - \lambda\mu H^2 > (1+\rho)+(1+\mu H)$, equilibrium is unique.

intermediate inputs (5.14) and the flow of profits from successful research rise. An increase in λ raises the probability of research success, while because research takes time (in the present case, one period) an increase in ρ reduces the expected return from research *relative* to intermediate input production.

A rise in θ increases the amount of secondary knowledge that spills over to the next fundamental innovation. Hence, the derived demand for intermediate inputs and the flow of profits from successful research both rise. A larger value of μ raises the rate of learning by doing, thereby increasing the period 2 wage in the production sector. As a result, the opportunity cost of entering the research sector rises and the flow of profits from successful research falls.

So far however, the analysis has been silent upon the implications of *pioneer* status for the quantity of resources devoted to the discovery of the next fundamental technology. The distinguishing feature of a pioneer of one fundamental technology is that she is characterised by a larger stock of secondary knowledge $S_{1,t}$ associated with that technology than an otherwise identical latestarter. From equation (5.19) and Figure 3, we may establish

Proposition 3 (i) *An increase in the stock of secondary knowledge associated with an existing fundamental technology* $S_{1,t}$ *may either* decrease *or* increase *equilibrium research employment* $\hat{n}_t$*, depending respectively upon whether the parameter* σ *is less than or greater than* 1.

(ii) *An increase in the supply of skilled labour* H *has an* ambiguous *effect upon equilibrium research employment* $\hat{n}_t$.

Proof. See Appendix.

Being a pioneer of one fundamental technology has an *ambiguous* effect upon the incentive to invest in research directed at the discovery of the next. If $\sigma < 1$, the elasticity of final goods output with respect to the accumulated stock of secondary knowledge $S_{1,t}$ is higher for the existing fundamental technology m than for the subsequent technology $m + 1$. Secondary knowledge is *more relevant* to the technology under which it is accumulated than for the subsequent technology, and each fundamental innovation induces *secondary knowledge obsolescence.* As a result, the larger stock of secondary knowledge $S_{1,t}$ implied by pioneer status *reduces* individuals' incentive to engage in research.

If $\sigma > 1$ exactly the converse is true. Secondary ideas *arrive before their time*, and the larger stock of secondary knowledge $S_{1,t}$ implied by pioneer status *raises* individuals' incentive to engage in research. Whether or not there is a *penalty* to being a pioneer in the first sense above depends upon the strength of secondary knowledge spillovers in production, i.e. whether secondary knowledge is rendered obsolete or ideas arrive before their time. A similar effect is present in the single agent model of Jovanovic and Nyarko (1994), where the question is a single agent's incentive to adopt a new technology. In the next Section, we extend the analysis to include knowledge spillovers in research, in which case the occurrence of secondary knowledge obsolescence is no longer sufficient for a penalty to being a pioneer to exist.

A second implication of Proposition 3 is that the supply of skilled labour H has an *ambiguous* effect upon equilibrium research employment. This is in marked contrast to the one-dimensional Schumpeterian models of endogenous growth surveyed in Chapter 2, which exhibit a *scale effect.* In both Romer (1990) and Aghion and Howitt (1992), an increase in the supply of skilled labour raises the quantity of research undertaken and the economy's rate of growth. However, once one admits that technological progress may occur in more than one-dimension, the analysis becomes less clear cut. On the one hand, an increase in the supply of skilled labour H has a *direct* effect of raising the quantity of resources available for fundamental research. On the other hand, an increase in H raises intermediate goods output and has the *indirect* effect of increasing the rate of learning by doing g. From equation (5.19) and Figure 3, an increase in the rate of learning by doing raises the opportunity cost of entering the research sector and reduces the flow of profits received by a successful researcher. Hence, equilibrium research employment may fall.

5.5 Knowledge Spillovers in Research

The research technology in equation (5.4) already embodies a knowledge spillover, in so far as each generation of researchers "stands upon the shoulders" of previous fundamental discoveries. In addition, it seems plausible that the secondary knowledge accumulated under one fundamental technology may be of relevance to research directed at the discovery of the next. The development of one fundamental technology may sow the seeds that lead to the discovery of the next. To take an example from the iron and steel industry, Henry Cort's "puddling and rolling" process (1784) that revolutionised the manufacture of wrought iron used ideas from a number of more minor innovations.[17]

In order to capture this idea, we allow the productivity of research λ to be a function of the stock of secondary knowledge accumulated under the existing fundamental technology. If $n_t \geq 0$ individuals enter the research sector in period 1, then we assume that with probability $\lambda(S_{1,t}).n_t$ *one* fundamental researcher discovers the next fundamental technology. The probability that a fundamental innovation occurs at the end of period 1 is thus,

$$\iota = \lambda(S_{1,t}).n_t, \tag{5.20}$$

$$\text{where: } \lambda(1) > 0, \quad \lambda'(S_{1,t}) > 0, \quad \lambda''(S_{1,t}) < 0 \quad \text{and} \quad 0 < \lim_{S_{1t} \to \infty} \lambda(S_{1,t}).H < 1,$$

Again, we assume that there are constant returns to scale in research. The existence of positive secondary knowledge spillovers in research is manifested in the assumption that $\lambda'(S_{1,t}) > 0$.

The determination of the equilibrium allocation of resources between intermediate input production and research is exactly as before. In an equilibrium characterised by both positive production and research, we require,

---

[17] Source: Mokyr (1990), pp. 93.

$$\underbrace{(1+\rho)+(1+g)}_{MC(n_t)}=\underbrace{\lambda(S_{1,t}).\left[\gamma^{\nu}.\theta.S_{1,t}^{\sigma-1}-(1+g)\right].[H-n_t]}_{MB(n_t)}, \tag{5.21}$$

$$\text{where:} \qquad g=\mu.(H-n_t),$$

Throughout the following, we assume that assumption 1 holds. In this case, the proof of existence and uniqueness of equilibrium is exactly as above. Comparative statics may be established in a directly analogous manner.

Proposition 4 *With knowledge spillovers in research, an increase in the stock of secondary knowledge associated with an existing fundamental technology $S_{1,t}$ again has an* **ambiguous** *effect on equilibrium research employment $\hat{n}_t$. A necessary and sufficient condition for $\hat{n}_t$ to be* **decreasing** *in $S_{1,t}$ is,*

$$\lambda'(S_{1,t}).\left[\gamma^{\nu}\theta S_{1,t}^{\sigma-1}-(1+g)\right]-(1-\sigma)\gamma^{\nu}\theta S_{1,t}^{\sigma-2}.\lambda(S_{1,t})<0,$$

Proof. See Appendix 1.

The effect of pioneer status upon the incentive to engage in research depends upon the extent of secondary knowledge spillovers in both the *production* and *research* sectors. Even if secondary knowledge is more relevant to final goods production with the current fundamental technology than with subsequent ones ($\sigma < 1$), a pioneer may still be characterised by higher equilibrium research employment if the accumulated stock of secondary knowledge raises the productivity of research $\lambda(S_{1,t})$ by a sufficiently large amount.

In order for a penalty to being a pioneer to exist in the sense of devoting less resources to the discovery of subsequent technologies, we require both that secondary knowledge obsolescence occur ($\sigma < 1$) and knowledge spillovers in research are sufficiently small ($\lambda'(S_{1,t})$ small).

5.6 Technological Lock-in

Of the two scenarios of *secondary knowledge obsolescence* and *ideas arriving before their time*, secondary knowledge obsolescence is perhaps the more plausible. In this case, Proposition 4 implies that, as long as knowledge spillovers in research are not too large, equilibrium research employment $\hat{n}_t$ will be a *decreasing* function of an economy's accumulated stock of secondary knowledge.

If the stock of secondary knowledge associated with the existing fundamental technology becomes sufficiently large, it is conceivable that an economy will not devote any resources to fundamental research at all, *even though research would be profitable in the absence of secondary innovation.* We term this phenomenon *technological lock-in.* As a result of its accumulated stock of secondary knowledge, an economy becomes *locked-into* an existing technology. Throughout this Section, we restrict consideration to parameter values satisfying the following assumptions.

Assumption 2 **(a)** $\hat{n}_t|_{S_{1,t}=1} > 0$,

(b) $\lambda'(S_{1,t}).\left[\gamma^{\nu}\theta S_{1,t}^{\sigma-1} - (1+g)\right] - (1-\sigma).\gamma^{\nu}\theta S_{1,t}^{\sigma-1}.\lambda(S_{1,t}) < 0,$

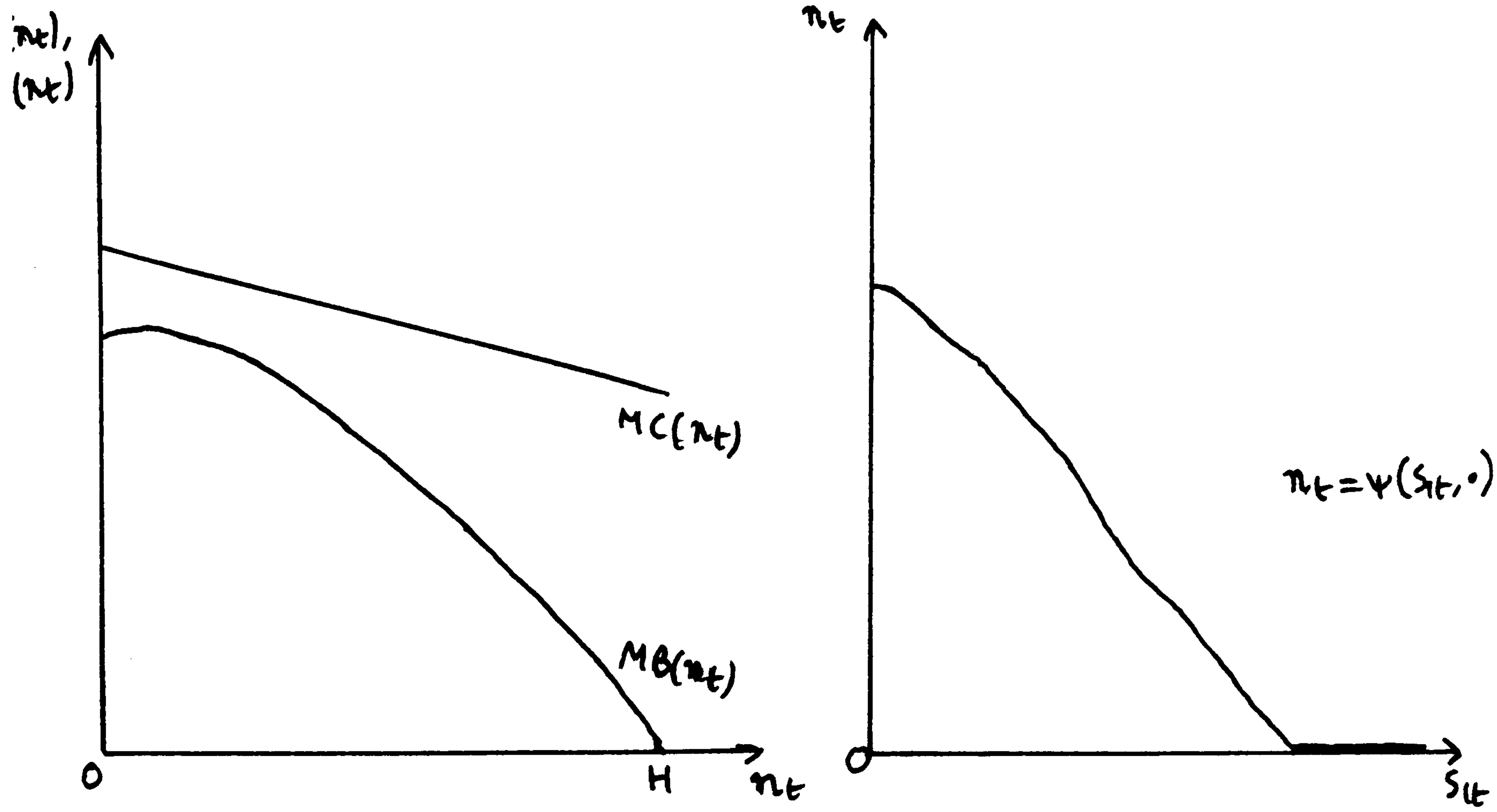
Assumption 2(a) simply requires that, in the absence of secondary innovation, equilibrium research employment $\hat{n}_t$ is indeed positive. Assumption 2(b) implies that knowledge spillovers in research are in fact not too large, and hence (from Proposition 4) $\hat{n}_t$ is a decreasing function of $S_{1,t}$.

Proposition 5 *Under assumptions 2(a) and 2(b),* **technological lock-in** *will occur whenever the stock of secondary knowledge accumulated under an existing fundamental technology $S_{1,t}$ is greater than or equal to a critical value $\tilde{S}_{1,t} > 1$. Where $\tilde{S}_{1,t}$ solves,*

$$S_{1,t} = \left[\frac{\gamma^{\nu}.\theta.H}{\frac{1}{\lambda(S_{1,t})}(1+\rho) + \left(\frac{1}{\lambda(S_{1,t})} + H\right)(1+\mu.H)}\right]^{\frac{1}{1-\sigma}},$$

Proof. See Appendix

Technological lock-in is the second form that the "penalty" to being a pioneer may take. A early-starter becomes locked-into an existing technology, while a latestarter continues to invest in research. Lock-in is illustrated in Figure 4(a), where (given the accumulated stock of secondary knowledge $S_{1,t}$) the marginal cost of research $MC(n_t)$ is strictly greater than the marginal benefit $MB(n_t)$ for all $n_t \in [0, H]$. Figure 4(b) plots equilibrium research employment as a function of the accumulated stock of secondary knowledge, and lock-in occurs for all $S_{1,t} \geq \tilde{S}_{1,t}$.



(a) (b)

FIGURE 4: Technological Lock-in

This phenomenon is not only a theoretical possibility: a number of apparent empirical examples of technological lock-in exist. Of these, David's (1985) example of the QWERTY keyboard is perhaps the most famous.[18] The QWERTY design was introduced in the 1870s to slow the rate at which individuals typed, and thereby reduce the frequency of the typebar clashes to which existing typewriters were prone. With current keyboard technology, typebar clashes are no longer a problem. Yet, despite the existence of a number of apparently superior alternatives, QWERTY remains the dominant keyboard design. One explanation for its continued use is the extent of secondary innovation, in the form of the development of "touch" typing in the 1880s and the acquisition of QWERTY specific skills by a large pool of typists.

Technological lock-in has received some attention in the microeconomics literature on technological progress (see for example Arthur (1989)). Brezis *et al.* (1993) find that lock-in may occur where the arrival of new technologies is exogenous, and Jovanovic and Nyarko (1994) obtain the same result in a single agent model of technology adoption. The present Section has shown that technological lock-in is possible in a general equilibrium model of endogenous growth. Its occurrence depends crucially upon the magnitude of secondary knowledge spillovers in both intermediate input production and research.

---

[18] Another apparent example is the widespread use of VHS Video Cassete Recorders instead of the alternative Betamax standard.

5.7 Equilibrium Growth

In the present general equilibrium framework, it is possible to solve for the economy's rate of growth. In order to keep the analysis as simple as possible, we return to the case where there are no secondary knowledge spillovers in research. That is, $\lambda(S_{1,t}) = \lambda$ and $\lambda'(S_{1,t}) = 0$. However, the analysis is readily extended to the more general case.

The economy's actual rate of growth is stochastic, depending upon whether or not a fundamental innovation occurs at the end of period 1. In this Section, we consider the expected or average rate of growth of equilibrium final goods output between the births of two succeeding generations t and $t+1$ (at the arbitrary points in time τ and $\tau+2$ respectively). Taking expectations over technologies at time τ in (5.2), we have,

$$\frac{\mathsf{E}_m Y_{\tau+2}}{Y_\tau} = \frac{\mathsf{E}_m Y_{1,t+1}}{Y_{1,t}} = \left(\frac{\mathsf{E}_m F^{\nu}_{1,t+1}}{F^{\upsilon}_{1,t}}\right)\cdot\left(\frac{\mathsf{E}_m S_{1,t+1}}{S_{1,t}}\right).\frac{\mathsf{E}_m\left(H-n_{t+1}\right)^{\alpha}}{(H-n_t)^{\alpha}}, \tag{5.22}$$

Taking logs, and evaluating expectations in the above, we obtain the following expression for the economy's expected or average rate of growth $\zeta_{t,t+1} = \log\left(\frac{\mathsf{E}_m Y_{1,t+1}}{Y_{1,t}}\right)$,

$$\begin{aligned}\zeta_{t,t+1} =&\underbrace{\log\left[\lambda\hat{n}_t(\gamma^{\upsilon}-1)+1\right]}_{A} + \underbrace{\log\left[\lambda\hat{n}_t.(1+g).\theta.S^{\sigma-1}_{1,t} + (1-\lambda\hat{n}_t).(1+g)^2\right]}_{B}\\ &+ \underbrace{\log\left[\lambda\hat{n}_t(H-\overline{n}_{t+1})^{\alpha} + (1-\lambda\hat{n}_t)(H-\underline{n}_{t+1})^{\alpha}\right] - \log\left[(H-\hat{n}_t)^{\alpha}\right]}_{C},\end{aligned} \tag{5.23}$$

$$\text{where} \qquad g = \mu.(H - \hat{n}_t),$$

The economy's expected rate of growth is composed of three terms. Firstly, there is the expected rate growth of fundamental knowledge F (term A in (5.23)). Secondly, there is the expected rate of growth of secondary knowledge S (term B). Thirdly, final goods output may grow because of changes in the expected flow of intermediate goods output $x = h$ across generations (term C).

The flow of intermediate goods output may change across generations as a result of the *reallocation* of labour from intermediate input production to research (since labour market clearing implies $h = H - n$). From Proposition 3, equilibrium research employment $\hat{n}_t$ in any generation t depends upon the stock of secondary knowledge that generation inherits. However, the stock of secondary knowledge inherited by generation t is endogenously determined by the rate of learning by doing and whether or not a fundamental innovation occurred during generation $t - 1$.

Thus, equilibrium research employment in generation $t + 1$ may take one of two values. If a fundamental innovation occurs during generation t, generation $t + 1$'s stock of secondary knowledge is given by $S_{1,t+1} = (1 + g).\theta.S^{\sigma}_{1,t}$ and equilibrium research employment by $\hat{n}_{t+1} = \overline{n}_{t+1} \equiv \psi\left(\left[(1 + g)\theta S^{\sigma}_{1,t}\right] , \cdot\right)$. Alternatively, if a fundamental innovation does not occur during generation t, the $t + 1$ stock of secondary knowledge is given by $S_{1,t+1} = (1 + g)^2.S_{1,t}$ and equilibrium research employment by $\hat{n}_{t+1} = \underline{n}_{t+1} \equiv \psi\left([(1+g)^2 S_{1,t}]\,,\,\cdot\,\right)$. The expected flow of intermediate goods output under generation $t+1$ may be either higher or lower than under generation t depending upon the relative values of $\overline{n}_{t+1}$, $\underline{n}_{t+1}$ and n_t.

The analysis that follows will be particularly concerned with the implications of pioneer status for the economy's rate of growth. In the exposition of comparative statics, we adopt the following convention. Firstly, we consider the effects of parameter changes on the economy's growth rate holding constant the values of equilibrium research employment in the two generations n_t, $\bar{n}_{t+1}$ and $\underline{n}_{t+1}$ (Proposition 6). Secondly, we allow equilibrium research employment in generation t to vary, holding constant equilibrium employment in generation $t+1$, $\bar{n}_{t+1}$ and $\underline{n}_{t+1}$ (Proposition 7). Finally, we allow both equilibrium research employment in generations t and $t+1$ to vary in response to parameter changes. This convention is purely for expository reasons. The total effect of any one parameter change on the economy's growth rate may be found simply by differentiating equation (5.23).

Proposition 6 *For given values of equilibrium research employment in the two generations, $\hat{n}_t$, $\bar{n}_{t+1}$ and $\underline{n}_{t+1}$, the economy's expected rate of growth is* increasing*:*

(A) (i) *The greater the size of fundamental innovations γ,* (ii) *The greater the elasticity of final goods output with respect to fundamental knowledge ν,* (iii) *The larger the knowledge spillover parameters θ and σ, (iv) The larger the learning by doing parameter μ.*

(B) *An increase in the stock of secondary knowledge associated with an existing fundamental* *technology $S_{1,t}$ may either* decrease *or* increase *the economy's expected rate of growth, depending respectively upon whether the parameter σ is less than or greater than* 1.

Proof. See Appendix.

Increases in both the size of fundamental innovations γ and the elasticity ν raise the contribution of each fundamental discovery to final goods output, and so raise the economy's expected rate of growth. An increase in either θ or σ raises the amount of secondary knowledge that spills over to a newly discovered fundamental technology, and so again raises the economy's expected rate of growth. The positive effect of the learning parameter μ upon the economy's growth rate reflects the essentially *complementary* nature of secondary innovation. Each secondary innovation raises the productivity of the existing stocks of both fundamental and secondary knowledge.

Pioneer status has an *ambiguous* effect upon the economy's rate of growth. In equations (5.22) and (5.23), an increase in the accumulated stock of secondary knowledge $S_{1,t}$ has three implications. Firstly, it raises the actual flow of final goods output produced in generation t (with an elasticity of 1). Secondly, it increases final goods output in generation $t+1$ in the event that fundamental research is unsuccessful (with elasticity 1). Finally, it also raises the flow of final goods output produced in generation $t+1$ in the event that a fundamental innovation occurs (with elasticity σ).

If $\sigma < 1$, then each fundamental innovation induces *secondary knowledge obsolescence.* An increase in the stock of secondary knowledge accumulated under an existing fundamental technology raises expected output in generation $t+1$ by proportionately less than it increases actual output in generation t. In this case, being a pioneer of a fundamental technology implies a *lower* expected rate of growth. However, if $\sigma > 1$ then exactly the converse applies. Secondary ideas *arrive before their time* and being a pioneer of a fundamental technology implies a higher expected rate of growth.

Proposition 7 *For given values of equilibrium research employment in generation* $t+1$, $\bar{n}_{t+1}$ *and* $\underline{n}_{t+1}$*:*

(i) *An increase in equilibrium employment in fundamental research during generation* t, $\hat{n}_t$, *has an* ambiguous *effect upon the economy's expected rate of growth,* (ii) *The effect of an increase in the productivity of research* λ *upon the expected rate of growth is* ambiguous.

Proof. See Appendix.

An increase in equilibrium research employment $\hat{n}_t$ affects the economy's growth rate in four ways. Firstly, it raises the expected rate of growth of fundamental knowledge (term A), and thereby *increases* the economy's rate of growth. Secondly, the increase in the probability that a fundamental innovation occurs at the end of period 1 also affects the expected rate of growth of secondary knowledge (term B). If $\sigma < 1$ and each fundamental innovation induces secondary knowledge obsolescence, then an increase in $\hat{n}_t$ will *lower* the economy's expected rate of growth. Thirdly, an increase in equilibrium research employment $\hat{n}_t$ reduces the rate of learning by doing g, thereby *reducing* the expected rate of growth of secondary knowledge (term B).

Finally, higher equilibrium research employment $\hat{n}_t$ affects the expected growth in intermediate goods output across generations. If $\sigma < 1$ and secondary knowledge obsolescence occurs, then the stock of secondary knowledge inherited by generation $t+1$, $S_{1,t+1}$, will be lower if fundamental research is successful during generation t than if not. As a result, from Proposition 3, equilibrium research employment in generation $t+1$ will be higher [equilibrium intermediate goods output will be lower] if a fundamental innovation occurs during generation t than if not, $\overline{n}_{t+1} > \underline{n}_{t+1}$. An increase in equilibrium research employment $\hat{n}_t$, increases the probability that generation $t+1$ research employment will be given by $\overline{n}_{t+1}$ rather than $\underline{n}_{t+1}$, thereby reducing the expected flow of intermediate goods output in generation $t+1$ and *reducing* the economy's expected rate of growth.

Of the two scenarios of *secondary knowledge obsolescence* and *ideas arriving before their time*, secondary knowledge obsolescence ($\sigma < 1$) is perhaps the most plausible. In this case, the negative sign of the second and fourth effects above reflects the fact that growth is essentially a process of *creative destruction.* While secondary innovations are entirely complementary, each fundamental innovation *substitutes* for an existing fundamental technology and its associated body of secondary knowledge. An increase in the productivity of fundamental research λ has exactly the same ambiguous effect upon the economy's expected rate of growth, except that in this case the learning by doing effect is absent.

In general, the implications of increase in fundamental research for the economy's average growth rate are ambiguous. Nonetheless, for sufficiently large values of the size of fundamental innovations γ, sufficiently small values of the learning parameter μ and sufficiently small values of the stock of secondary knowledge $S_{1,t}$, the economy's average growth rate will be *increasing* in equilibrium research employment $\hat{n}_t$.[19]

Since the average growth rate depends upon $\hat{n}_t$, each of the parameters which influence equilibrium research employment in Propositions 2 and 3 will have *indirect* effects upon the economy's expected rate of growth. If secondary knowledge obsolescence occurs ($\sigma < 1$), Proposition 3 implies that a pioneer of a fundamental technology will be characterised by a lower level of equilibrium research employment than a latestarter. If the economy's average growth rate is increasing in $\hat{n}_t$, then a "penalty" to being a pioneer in the sense of lower equilibrium research employment will translate into a "penalty" to being a pioneer in terms of a lower expected rate of growth.

Thus, pioneer status has both a *direct* effect upon the economy's average rate of growth through the size of secondary knowledge spillovers (Proposition 6) and an *indirect* effect through equilibrium research employment (Propositions 3 and 7). A sufficient condition for a pioneer

---

[19] A sufficient condition for the expected rate of growth to be increasing in $\hat{n}_t$ is given in the proof of Proposition 7.

to be characterised by a lower expected rate of growth than an otherwise identical latestarter is for secondary knowledge obsolescence to occur ($\sigma < 1$) and for the economy's growth rate to be increasing in $\hat{n}_t$. As argued earlier, if such a "penalty" to being a pioneer exists, it provides one potential explanation for relative economic decline and income convergence (see also the discussion in Chapter 7).

Throughout the analysis of Propositions 6 and 7, we have taken the values of equilibrium research employment in generation $t+1$ in the cases where research is successful and unsuccessful in generation t ($\overline{n}_{t+1}$ and $\underline{n}_{t+1}$ respectively) as given. In fact, these values are endogenously determined. Equilibrium research employment in generation $t+1$ is given by equation (5.19), substituting for the value of $S_{1,t+1}$ for the cases where research is successful and unsuccessful in generation t. Hence, as defined above $\overline{n}_{t+1} \equiv \psi\left(\left[(1+g)\theta S^{\sigma}_{1,t}\right] \ , \ \cdot\right)$ and $\underline{n}_{t+1} \equiv \psi\left(\left[(1+g)^2 S_{1,t}\right] \ , \ \cdot\ \right)$. Using Propositions 2 and 3, it is straightforward to extend the analysis to allow each parameter change to affect both $\overline{n}_{t+1}$ and $\underline{n}_{t+1}$. For example, an increase in the learning parameter μ raises the stock of secondary knowledge inherited by generation $t+1$ independent of whether research is successful or not. Hence, in the case of secondary knowledge obsolescence ($\sigma < 1$) both $\overline{n}_{t+1}$ and $\underline{n}_{t+1}$ will fall, raising the flow of intermediate goods output produced by generation $t+1$ and increasing the economy's expected rate of growth across the two generations.

From equation (5.23), the expression for the economy's expected rate of growth is particularly straightforward in the equilibrium characterised by technological lock-in. In this case, no individual chooses to undertake fundamental research, $\hat{n}_t = \hat{n}_{t+1} = 0$, and,

$$\zeta_{t,t+1} = \log\left[(1+g)^2\right], \qquad \text{where} \quad g = \mu.H, \tag{5.24}$$

In the present specification, learning by doing is technologically unbounded and secondary knowledge accumulation may be a source of endogenous growth. However, by definition secondary innovations are minor improvements to an existing technology. Hence, it is plausible that μ is small relative to γ, and that the economy's expected rate of growth is *lower* in the case technological lock-in than in an equilibrium characterised by positive research employment. Whenever technological lock-in occurs, a "pioneer" of a fundamental technology thus becomes trapped in a "low growth" equilibrium.

5.8 Welfare Analysis

The analysis so far has been concerned with whether or not there is a "penalty" to being a pioneer in terms of devoting less resources to fundamental research, becoming locked-into an existing technology, or experiencing a slower rate of economic growth. In this Section, we turn to consider the fourth sense of the "penalty" to being a pioneer identified above: namely, whether a pioneer enjoys a lower level of *economic welfare* than an otherwise identical latestarter. We address the issue by considering under what circumstances it would ever be optimal for a pioneer to destroy or render obsolete a portion of its accumulated stock of secondary knowledge.

This question has been a concern of the economic history literature for some time. A number of authors have argued that one of the explanations for Germany and Japan's rapid growth in the post World War II period is the destruction and upheaval associated with being on the losing side in the war. Often it is argued that allied bombing attacks destroyed obsolete capital equipment or that defeat weakened incumbent interest groups and destroyed existing modes of organisation.[20] In terms of the present framework, this corresponds to the destruction or obsolescence of secondary knowledge associated with an existing fundamental technology. The analysis of the previous Section, provides a reason why this obsolescence might (though need not necessarily) accelerate growth. Throughout this Section, we assume that there is a "penalty" to being a pioneer in the sense of a lower rate of growth of GDP per capita. However, even if the destruction of secondary knowledge (being on the losing side of a war) accelerates growth, it need not necessarily increase economic welfare.

Consider the problem of a social planner choosing the fraction ε, $0 \leq \varepsilon \leq 1$, of the stock of accumulated secondary knowledge $S_{1,t}$ to destroy in order maximise the welfare of a generation t. The social planner chooses ε subject to the final goods and intermediate input technologies (5.2) and (5.3), and subject to the no-arbitrage condition (5.19) determining equilibrium research

---

[20] See for example Olson (1982). Ben-David and Papell (1995) provide econometric evidence that Japan, Norway, Austria, Belgium, Denmark, France, Germany, Italy, the Netherlands and Switzerland all experienced post World War II structural breaks in per capita GDP. In each of these economies, the post-break is associated with a higher rate of economic growth.

employment. The social planner's problem is thus,

$$\max_{\varepsilon} \hat{Y}_{1,t} + \left(\frac{1}{1+\rho}\right) \mathsf{E}\left[\hat{Y}_{2,t}\right], \tag{5.25}$$

where,

$$\hat{Y}_{1,t} = F^{\nu}_{1,t}.(1-\varepsilon).S_{1,t}.\,(H - \hat{n}_t(\varepsilon))^{\alpha}$$

$$\mathsf{E}\left[\hat{Y}_{2,t}\right] = \lambda \hat{n}_t(\varepsilon).\left[\gamma^{\nu}\theta(1-\varepsilon)^{\sigma-1} S^{\sigma-1}_{1,t} \hat{Y}_{1,t}\right] + (1-\lambda\hat{n}_t(\varepsilon))\,.\left[(1+g)\hat{Y}_{1,t}\right] \quad ,$$

subject to the following constraints,

$$\varepsilon \in [0,1],$$

$$\hat{n}_t(\varepsilon) \quad \text{solves} \quad \underbrace{(1+\rho)+(1+g)}_{MC(n_t)} = \underbrace{\lambda.\left[\gamma^{\nu}.\theta.\left[(1-\varepsilon)S_{1,t}\right]^{\sigma-1} - (1+g)\right].\left[H - n_t\right]}_{MB(n_t)}, \tag{5.26}$$

where $g = \mu.(H - n_t)$. From the first-order condition to this problem we obtain,

$$\underbrace{\lambda\frac{\partial \hat{n}_t}{\partial \varepsilon}.\Gamma}_{\text{Term } D} - \underbrace{\lambda.\frac{\partial \hat{n}_t}{\partial \varepsilon}(1+g)(1-\varepsilon)}_{\text{Term } E} \leq \underbrace{(1+\rho)\left[1+\alpha\frac{\partial \hat{n}_t}{\partial \varepsilon}(1-\varepsilon)(H-\hat{n}_t)^{-1}\right]}_{\text{Term } F}$$

$$+ \underbrace{\left[\sigma\lambda\hat{n}_t(1-\varepsilon)^{-1}\Gamma + (1-\lambda\hat{n}_t)(1+g)\right]}_{\text{Term } G} \tag{5.27}$$

$$+ \underbrace{\alpha\frac{\partial \hat{n}_t}{\partial \varepsilon}.\left[\lambda\hat{n}_t\Gamma + (1-\lambda\hat{n}_t)(1+g)(1-\varepsilon)\right](H-\hat{n}_t)^{-1}}_{\text{Term } H},$$

$$\varepsilon \geq 0, \qquad \text{with at least one equality,}$$

where $\Gamma \equiv \gamma^{\nu}.\theta.(1-\varepsilon)^{\sigma}.S_{1,t}^{\sigma-1}$. For the destruction of secondary knowledge to be welfare increasing, we require that the left-hand side of (5.27) evaluated at $\varepsilon = 0$ exceeds the right-hand side evaluated at $\varepsilon = 0$.

The first effect of the destruction of secondary knowledge is to raise equilibrium research employment $\hat{n}_t$. On the one hand, this raises period 2 output because of the increased probability of a fundamental innovation being made (term D). On the other hand, this positive effect on expected period 2 output is partly mitigated by the increased probability of secondary knowledge obsolescence occurring (term E).

However, the second effect of the destruction of secondary knowledge is to reduce period 1 output. From (5.2), secondary knowledge obsolescence has a direct negative effect on final goods output through the associated reduction in the productivity of intermediate inputs, and also a negative indirect effect as the induced rise in research employment reduces the flow of skilled labour available for intermediate input production (term F). These direct and indirect level effects are repeated in period 2, as manifested in terms G and H respectively in (5.27).

The destruction of secondary knowledge accelerates *growth.* However, growth is both a process of destruction as well as creation. Furthermore, while such a policy accelerates growth, it also reduces current and future *levels* of final goods output. In order for the policy to be welfare improving, we require that term D exceed the combined effect of terms E, F, G and H. It is thus *possible* for the destruction of secondary knowledge (in for example a war) to be welfare improving.[21] However, it is implausible. Furthermore, for sufficiently large values of the subjective rate of time preference ρ and the rate of secondary innovation g, or for sufficiently small values of research productivity λ, the right-hand side of (5.27) will exceed the left-hand side for all $\varepsilon \in (0,1]$. In these circumstances, the destruction of secondary knowledge can never be welfare increasing.

5.9 Bounded Learning by Doing

In general, it is plausible that the extent of incremental improvement that can occur with any one fundamental technology is limited or *bounded.* In this Section, we consider an extension of the basic analysis to the case where secondary innovation takes the form of bounded learning by doing. All the results of this Chapter remain robust to this extension, and in particular technological lock-in may still occur.

---

[21] In the analysis so far, a war has been associated solely with the destruction of secondary knowledge. In reality of course, there are a number of other effects (including the destruction of fundamental knowledge), which mean that a war is likely to be welfare reducing.

Thus, suppose that the learning by doing technology in equation (5.6) is replaced with the following specification, which follows Parente (1994). If a fundamental technology is employed for two consecutive periods j and $j-1$, then,

$$S_j - S_{j-1} = \mu - \delta . S_{j-1}, \qquad \mu > 0, \qquad 0 < \delta < 1, \tag{5.28}$$

The rate of learning by doing is now given by $g = \frac{S_j - S_{j-1}}{S_{j-1}} = \frac{\mu}{S_{j-1}} - \delta$, and falls monotonically as secondary knowledge accumulates over time. For simplicity, the rate of learning by doing is assumed to be independent of the flow of intermediate goods output. Under the above specification, the stock of secondary knowledge is bounded above $\hat{S} = \mu/\delta$.

The analysis of the preceding Sections may now be repeated for the case of bounded learning by doing. In an equilibrium characterised by positive production and research, we require that individuals are indifferent between the two sectors. Equilibrium research employment $\hat{n}_t$ is determined by (5.19), where $g = \frac{\mu}{S_{j-1}} - \delta$. In the present case, the rate of learning by doing is independent of intermediate goods output and hence equilibrium is unique.

The comparative statics in Propositions 2 and 3 may be repeated, and the analysis may be extended to include research spillovers as in Proposition 4. From Proposition 5, technological lock-in will occur if and only if the stock of secondary knowledge $S_{1,t}$ inherited by a generation is greater than or equal to a critical value $\tilde{S}_{1,t}$. In the absence of knowledge spillovers in research, then, from equation (5.19), $\tilde{S}_{1,t}$ is given by,

$$\tilde{S}_{1,t} = \left[\frac{\gamma^{\nu}.\theta.H}{\frac{1}{\lambda}.(1+\rho) + \left(\frac{1}{\lambda} + H\right).(1+g)} \right]^{\frac{1}{1-\sigma}}, \tag{5.29}$$

Whether or not technological lock-in is possible with bounded learning by doing, will depend upon whether the accumulated stock of secondary knowledge $S_{1,t}$ may exceed the critical value $\tilde{S}_{1,t}$. From equation (5.28), we may solve for the evolution of the stock of secondary knowledge across generations. Denote the number of generations since the discovery of the current state of the art fundamental technology m by $\phi \in [1, \infty)$. Then,

$$S_{1,\phi+1}(m) = (2-\delta).\mu + (1-\delta)^2.S_{1,\phi}(m), \tag{5.30}$$

The stock of secondary knowledge evolves according to a first-order linear difference equation. From (5.30),

$$S_{1,\phi} = \Omega. \left[(1-\delta)^2\right]^{\phi} + \frac{(2-\delta)\mu}{[1-(1-\delta)^2]}, \tag{5.31}$$

Ω is determined by the initial condition $S_{1,1}(m) = \mu + (1-\delta).\theta\bar{S}(m-1)^{\sigma}$, where $\bar{S}(m-1)$ denotes the value of the secondary knowledge stock associated with the previous fundamental technology $m-1$ at the time technology m was discovered. Under the assumption $0 < \delta < 1$, the stock of secondary knowledge converges monotonically from its initial value to a steady-state value $\hat{S}_1 = \frac{(2-\delta)\mu}{[1-(1-\delta)^2]}$, as shown in Figure 5. Even though learning by doing is bounded, technological lock-in may occur if $\hat{S}_{1,t} \geq \tilde{S}_{1,t}$. In some sense, technological lock-in will be less likely, in so far as the rate of learning by doing (and hence the rate of growth in $S_{1,t}$) falls over time.

5.10 Temporary Lock-in

Throughout the analysis above, the parameters σ and θ determine the extent of secondary knowledge spillovers across fundamental technologies. Together they may be thought of as parameterising the degree of *complementarity* between fundamental innovations or the extent of *creative destruction.*[22] In the absence of knowledge spillovers in research, then $\sigma < 1$ is a sufficient condition for there to be a penalty of a pioneer in terms of lower equilibrium research employment. If the accumulated stock of secondary knowledge becomes sufficiently large, then, as we have seen, permanent technological lock-in may occur in both the case of unbounded and bounded learning by doing.

In general, the magnitude of secondary knowledge spillovers will vary across fundamental technologies and will be unknown prior to discovery of a fundamental technology. Some technologies will be extremely complementary (e.g. there may have been large spillovers of typing skills from typewriters to computers), while others (e.g. the internal combustion engine and nuclear power) will be less so. In this Section, we return to the case of *un*bounded learning

---

[22] For an alternative approach to the degree of substitutability and complementarity between innovations, based in the nature of horizontal differentiation rather than the distinction between fundamental and secondary innovation, see Young (1993b).

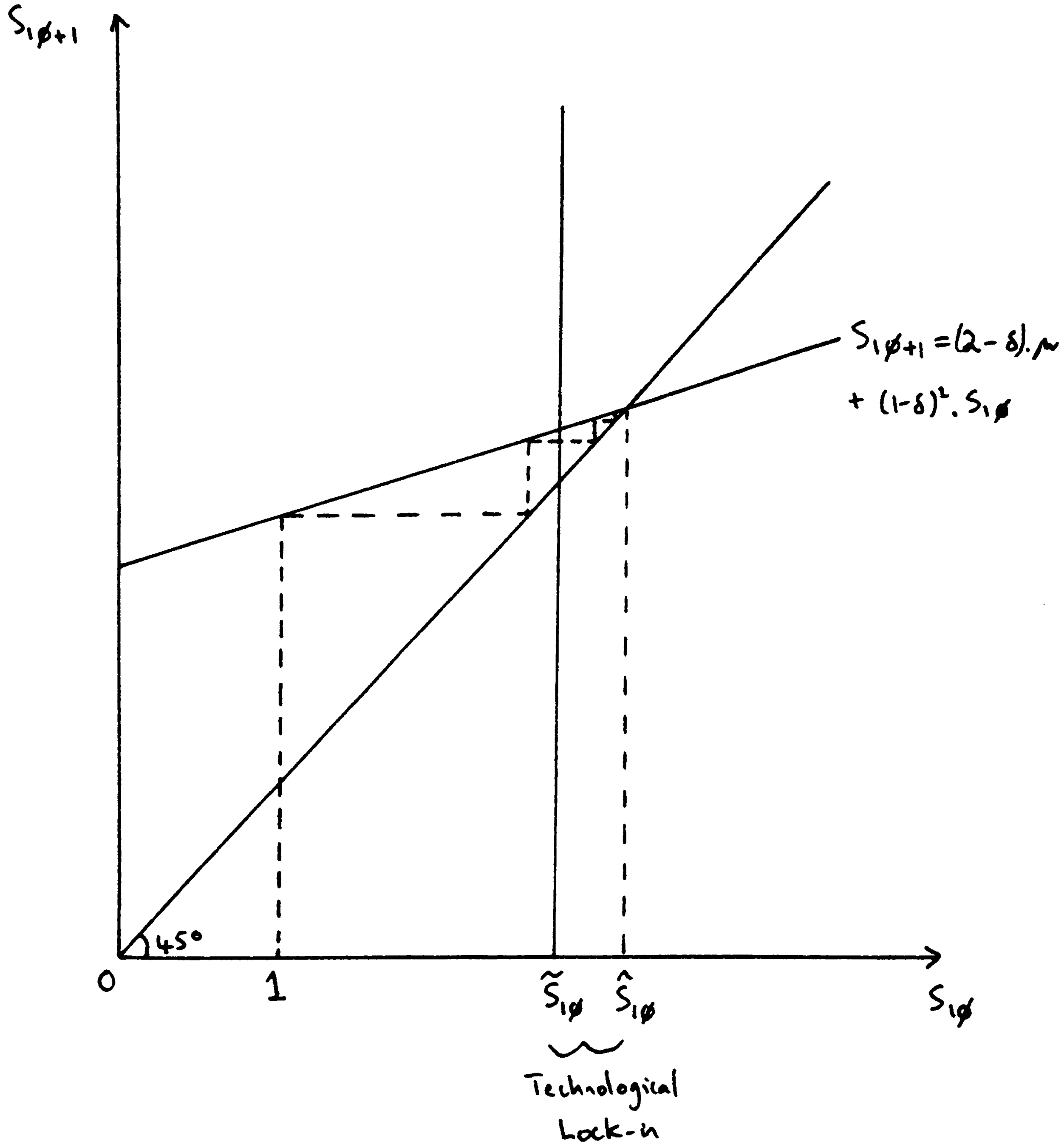


Figure 5: Bounded Learning by Doing.

by doing and extend the previous analysis to allow for such variations in the size of secondary knowledge spillovers.

Suppose the knowledge spillover parameter θ is a random variable, uniformly distributed with support $[\underline{\theta}, \overline{\theta}] \subset [0, 1]$.[23] Since agents are risk neutral, the equilibrium amount of fundamental research will be determined by the expected value of θ, $\theta_e = \frac{\overline{\theta} - \underline{\theta}}{2}$. Equilibrium research employment is determined by equation (5.19), where we replace the (now unknown) value of θ with its expectation θ_e. Under the assumption that $\gamma^v.\theta_e.S_{1,t}^{\sigma-1} > 1 + g$ and $\lambda H. \left[\gamma^\nu.\theta_e.S_{1,t}^{\sigma-1} - 1\right] - \mu H.(1 + \lambda H) > 2 + \rho$, Proposition 1 implies that a unique interior equilibrium allocation of skilled labour between research and production $[\hat{n}_t, (H - \hat{n}_t)]$ exists.

While equilibrium research employment is determined by the *expected* value of θ, θ_e, the decision whether or not to adopt a fundamental technology once research is successful is determined by the *realised* value θ_r. From equation (5.16), we may define a critical value of θ, θ_c, such that for all values of $\theta < \theta_c$ the period 2 flow of profits from intermediate input production with the new fundamental technology is strictly negative. From (5.16), θ_c solves,[24]

$$\gamma^v.\theta_c.S_{1,t}^{\sigma-1} = 1 + g, \tag{5.32}$$

Even if research is successful, then a new fundamental technology either may or may not be adopted in the intermediate input sector, depending upon whether $\theta_r > \theta_c$ or $\theta_r < \theta_c$

---

[23] Clearly, σ may also be a random variable. However, for simplicity, we continue to treat it as a parameter.

[24] where, from the above, $\theta_c < \theta_e$.

respectively. A distinction emerges between the decision to undertake *research* and the decision to *adopt* a fundamental technology if research is successful. *Temporary* technological lock-in may occur, where even though a more productive (in terms of fundamental knowledge) technology has been discovered, $\theta_r < \theta_c$ and the new fundamental technology is not adopted.

Temporary technological lock-in is explained by the secondary knowledge obsolescence that would be induced by the adoption of the new fundamental technology. On average, the extent of secondary knowledge obsolescence is not sufficient to render research unprofitable. However, for bad realisations of the size of secondary knowledge spillovers, it will not be profitable to adopt the new fundamental technology.

From equation (5.32), the critical value of θ below which temporary lock-in occurs is a function of the accumulated stock of secondary knowledge $S_{1,t}$. Under the assumption $\sigma < 1$, secondary knowledge is *more relevant* to the existing fundamental technology than to subsequent ones, and θ_c is monotonically decreasing in $S_{1,t}$. Hence, given the distribution for θ, a pioneering economy will be *more likely* not to adopt a newly discovered fundamental technology than an otherwise identical latestarter.

Throughout the analysis of this Section, the distribution for θ has been taken given. In reality, the latter may, at least in part, be determined by economic decisions. One reason often cited for the rapid growth of Japanese manufacturing industry is its flexibility, as determined for example by use of Just-in-Time (JIT) Production and Flexible Manufacturing Systems (FMS).

JIT and FMS may be thought innovations that are even more "fundamental" than what we have termed fundamental innovations ("meta"-innovations). As such, they may affect both the quality or productivity of intermediate inputs, and the flexibility of industry in adopting fundamental innovations. That is, JIT and FMS may have induced an outward movement in the support of θ. From Propositions 2 and 6, the larger θ, the higher equilibrium research employment and the higher the economy's expected rate of growth.

5.11 Conclusion

The present Chapter has sought to identify in what sense and in what circumstances there might be a "penalty" to being a pioneer in a general equilibrium model of endogenous growth. Following Aghion and Howitt (1996a), a distinction was drawn between fundamental innovations (major breakthroughs) on the one hand, and secondary innovations (incremental improvements) on the other.

A pioneer is the first economy to innovate or discover a particular fundamental technology. Hence, in general, it will be characterised by a higher stock of secondary knowledge specific to that technology. At least four potential forms of the penalty to being a pioneer were identified: a reduced incentive to innovate, a lower rate of output growth, technological lock-in and a lower level of economic welfare.

Whether or not there is a penalty to being a pioneer in the first three senses depends on the one hand upon the size of secondary knowledge spillovers in *production*, and on the other hand upon the size of these spillovers in *research.* In the most plausible case, the secondary knowledge accumulated under one fundamental technology is more relevant to that technology than the next ($\sigma < 1$). Secondary knowledge spillovers are imperfect, and each fundamental innovation induces *secondary knowledge obsolescence.*

In this case, unless secondary knowledge spillovers in research ($\lambda'(S_{1,t})$) are sufficiently large, a pioneer will devote less resources to Research and Development (R & D) than an otherwise identical latestarter. If fundamental innovations are sufficiently drastic, lower equilibrium research employment will translate into a lower expected rate of growth. In this case, pioneer status reduces an economy's rate of growth both directly (because of the increased potential for secondary knowledge obsolescence) and indirectly through reduced research employment.

If the accumulated stock of secondary knowledge becomes sufficiently large, a pioneering economy will become permanently *locked-into* an existing technology. This equilibrium constitutes a low-growth trap, and lock-in is possible both in the case of bounded and unbounded learning by doing. One interpretation of the size of secondary knowledge spillovers in production is that it is a measure of the degree of complementarity between fundamental technologies. Whenever the magnitude of these secondary knowledge spillovers varies across fundamental technologies, research and adoption decisions are separated and *temporary* lock-in becomes possible.

While secondary knowledge obsolescence is the most plausible case, it is also possible that *ideas arrive before their time.* In this case, $\sigma > 1$ and the secondary knowledge acquired under one fundamental technology is of more relevance to the next fundamental innovation than to the technology under which it was acquired. For sufficiently large values of σ and θ, all of the comparative static results are reversed. A pioneer is characterised by higher equilibrium research employment, a higher expected rate of growth and technological lock-in is no longer possible. Thus, whether or not there is a penalty to being a pioneer in all three positive senses is really an empirical question. Interestingly, if there is such a penalty to being a pioneer, it provides an alternative explanation for income convergence to those suggested in the existing literature.

Even if pioneer status is associated with lower equilibrium research employment and a lower rate of economic growth, it is implausible that it will reduce the economic welfare of a representative agent. Hence, it is implausible that any measure or event (such as a war) that reduces the existing stock of secondary knowledge will be welfare improving. On the one hand, the destruction of secondary knowledge raises research employment and the probability of a fundamental innovation. On the other hand, it reduces the level of final goods output and increases the probability of secondary knowledge obsolescence occurring.

5.12 Appendix: Proof of Propositions

Proof of Lemma 1

From equation (5.19),

$$\frac{\partial MB(n_t)}{\partial n_t} = 2.\lambda.\mu.(H - n_t) - \lambda.\left[\gamma^{v}.\theta.S_{1t}^{\sigma-1} - 1\right], \tag{5.33}$$

where, by assumption, $\gamma^{v}.\theta.S_{1t}^{\sigma-1} > 1 + g \geq 1$. From (5.33),

$$\frac{\partial MB(n_t)}{\partial n_t} > 0 \quad \Leftrightarrow \quad n_t < n_t^c \equiv H - \frac{1}{2\mu}.\left[\gamma^{\nu}.\theta.S_{1t}^{\sigma-1} - 1\right],$$

$$\frac{\partial MB(n_t)}{\partial n_t} = 0 \quad \Leftrightarrow \quad n_t = n_t^c \equiv H - \frac{1}{2\mu}.\left[\gamma^{\nu}.\theta.S_{1t}^{\sigma-1} - 1\right],$$

$$\frac{\partial MB(n_t)}{\partial n_t} < 0 \quad \Leftrightarrow \quad n_t > n_t^c \equiv H - \frac{1}{2\mu}.\left[\gamma^{\nu}.\theta.S_{1t}^{\sigma-1} - 1\right],$$

□

Proof of Proposition 1

The proof follows in two stages. In (i), we prove that, under assumption 1, an interior equilibrium must exist. In (ii), we prove that, under assumption 1, this equilibrium is unique.

(i) From equation (5.19), $MC(n_t)|_{n_t=0} > MC(n_t)|_{n_t=H} > 0$. Under assumption 1, $MB(n_t)|_{n_t=0} > MC(n_t)|_{n_t=0}$. While, from equation (5.19), $MC(n_t)|_{n_t=H} > MB(n_t)|_{n_t=H} = 0$. Hence, since both $MB(n_t)$ and $MC(n_t)$ are continuous functions of n_t, at least one interior equilibrium must exist.

(ii) However, from equation (5.19), $MC(n_t)$ is monotonically decreasing in n_t over the interval $[0, H]$. While, from lemma 1, $MC(n_t)$ is monotonically increasing in n_t over the interval $n_t \in [0, n_t^c)$ (where $n_t^c < H$) and monotonically decreasing in n_t over the interval $n_t \in (n_t^c, H]$. Hence, as shown in Figure 6, the interior equilibrium is unique. □

Proof of Proposition 2

Proposition 2 may be proved graphically using Figure 3. Increases in λ, γ, θ and ν raise the marginal benefit of research $MB(n_t)$ while leaving the marginal cost unaffected. Hence, equilibrium research employment $\hat{n}_t$ must rise. Increases in ρ raise the marginal cost of research while leaving the marginal benefit unaffected, hence $\hat{n}_t$ must fall. A rise in μ increases the marginal cost of research while simultaneously decreasing the marginal benefit, hence again $\hat{n}_t$ falls. □

Proof of Proposition 3

Proposition 3 may be proved using equation (5.19) and Figure 3.

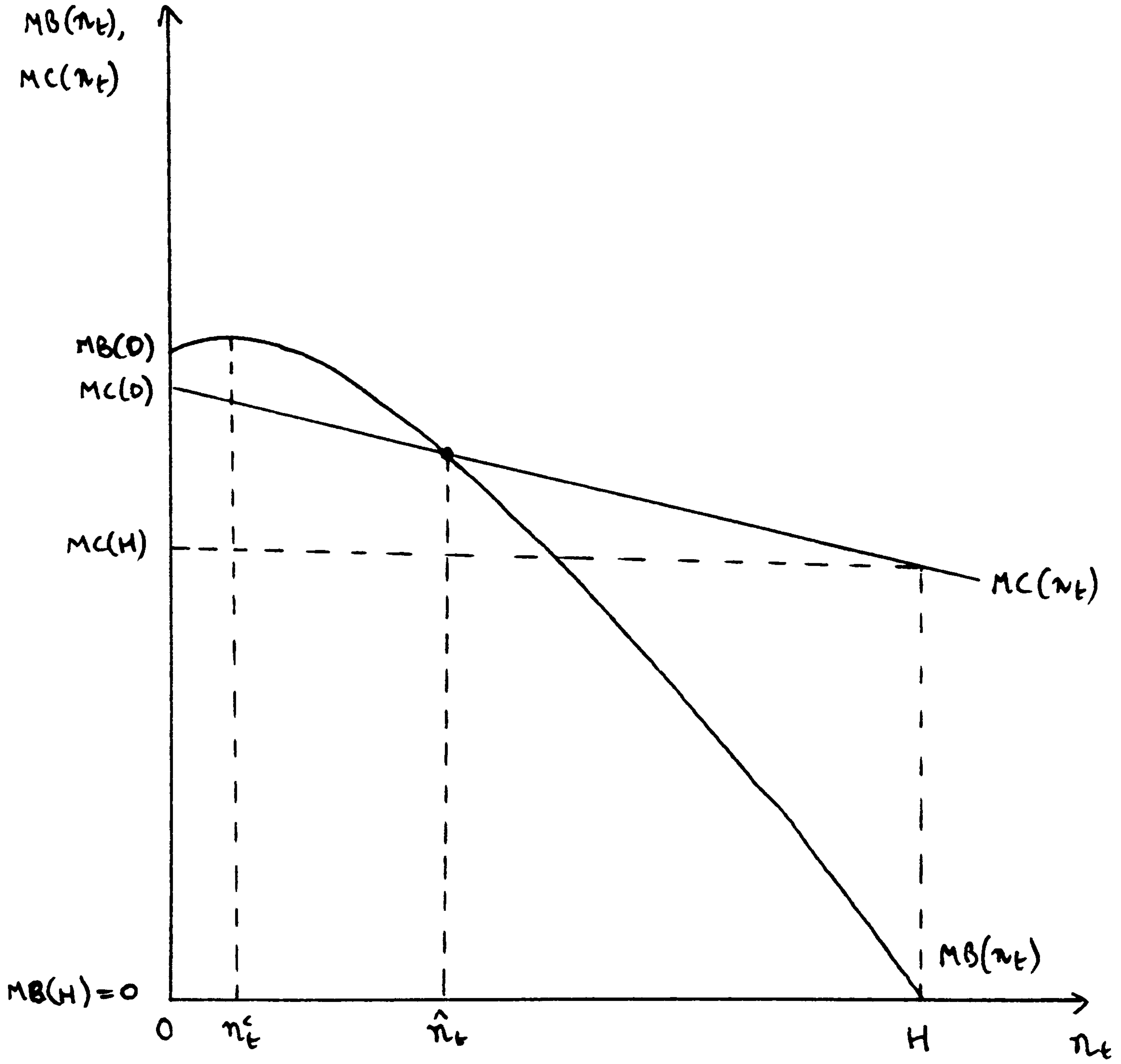


Figure 6: Proof of Proposition 1

(i) Assume $\sigma < 1$, then $\frac{\partial MB(n_t)}{\partial S_{1,t}} < 0$. Increases in the stock of secondary knowledge associated with an existing fundamental technology $S_{1,t}$ reduce the marginal benefit from research, while leaving the marginal cost unchanged. Hence, equilibrium research employment $\hat{n}_t$ falls. Assume $\sigma > 1$, then $\frac{\partial MB(n_t)}{\partial S_{1,t}} > 0$. Increases in the stock of secondary knowledge associated with an existing fundamental technology $S_{1,t}$ increase the marginal benefit from research, while leaving the marginal cost unchanged. Hence, equilibrium research employment $\hat{n}_t$ rises.

(ii) An increase in the supply of skilled labour H raises intermediate input employment $(H - n_t)$ for a given value of n_t. From equation (5.19) and Figure 3, an increase in $(H - n_t)$ raises the rate of learning by doing and increases the marginal cost of research. In contrast, the effect of an increase in $(H - n_t)$ upon the marginal benefit of research is ambiguous. Hence, equilibrium research employment may either rise or fall. $\square$

Proof of Proposition 4

Proposition 4 may be proved using equation (5.21) and Figure 3. An increase in the stock of secondary knowledge $S_{1,t}$ leaves the marginal cost of research unchanged. However, from equation (5.21), an increase in $S_{1,t}$ may either raise or lower the marginal benefit of research, depending upon the sign of,

$$\frac{\partial MB(n_t)}{\partial S_{1,t}} = \lambda'(S_{1,t}).\Phi.\left[H - n_t\right] - (1-\sigma).\gamma^{\nu}\theta S_{1,t}^{\sigma-2}.\lambda(S_{1,t})\left[H - n_t\right],$$

$$\text{where} \qquad \Phi \equiv \gamma^{\nu}\theta S_{1,t}^{\sigma-1} - (1+g),$$

A necessary and sufficient condition for equilibrium research employment $\hat{n}_t$ to be decreasing in $S_{1,t}$ is $\frac{\partial MB(n_t)}{\partial S_{1,t}} < 0$,

$$\Leftrightarrow \qquad \lambda'(S_{1,t}).\left[\gamma^{\nu}\theta S_{1,t}^{\sigma-1} - (1+g)\right] - (1-\sigma)\gamma^{\nu}\theta S_{1,t}^{\sigma-2}.\lambda(S_{1,t}) < 0,$$

□

Proof of Proposition 5

By assumption $\hat{n}_t|_{S_{1,t}=1} > 0$, while (from Proposition 4) assumption 2(b) implies $\frac{\partial \hat{n}_t}{\partial S_{1,t}} < 0$. From equation (5.19),

$$\hat{n}_t|_{S_{1,t}} = 0 \qquad \Leftrightarrow \qquad S_{1,t} \geq \tilde{S}_{1,t},$$

where $\tilde{S}_{1,t}$ solves,

$$S_{1,t} = \left[\frac{\gamma^{\nu}.\theta.H}{\frac{1}{\lambda(S_{1,t})}(1+\rho) + \left(\frac{1}{\lambda(S_{1,t})} + H\right)(1+\mu.H)}\right]^{\frac{1}{1-\sigma}}, \tag{5.34}$$

The right hand side of (5.34) is monotonically increasing in $S_{1,t}$, and bounded below by $\left[\frac{\gamma^{\nu}.\theta.H}{\lambda(1)^{-1}.(1+\rho)+(\lambda(1)^{-1}+H)(1+\mu.H)}\right]^{1/1-\sigma} > 0$. From equation (5.20), $\lim_{S_{1,t}\to\infty} \lambda(S_{1,t}) < 1/H$. The right hand side of (5.34) is thus bounded above by $0 < \left[\frac{\gamma^{\nu}.\theta.H}{\lambda(1/H)^{-1}.(1+\rho)+(\lambda(1/H)^{-1}+H)(1+\mu.H)}\right]^{1/1-\sigma} < +\infty$. As shown in Figure 7, existence and uniqueness of $\tilde{S}_{1,t}$ follows immediately. □

Proof of Proposition 6

(A) and (B) follow immediately from partially differentiating equation (5.23) with respect to the parameter of interest, taking $\hat{n}_t$, $\overline{n}_{t+1}$ and $\underline{n}_{t+1}$ as given. □

Proof of Proposition 7

(i) follows immediately from partially differentiating (5.23) with respect to $\hat{n}_t$, taking $\overline{n}_{t+1}$ and $\underline{n}_{t+1}$ as given. From (5.23), a *sufficient* condition for the economy's expected rate of growth to be *increasing* in $\hat{n}_t$ is,

$$\frac{\lambda\,(\gamma^{\nu}-1)}{\lambda\hat{n}_t\,(\gamma^{\nu}-1)+1}-\frac{\lambda(1+g)\theta S_{1,t}^{\sigma-1}-\lambda(1+g)^2-\mu\left(\lambda\hat{n}_t\theta S_{1,t}^{\sigma-1}+(1-\lambda\hat{n}_t)2(1+g)\right)}{\lambda\hat{n}_t.(1+g)\theta S_{1,t}^{\sigma-1}+(1-\lambda\hat{n}_t)(1+g)^2}>0,$$

(ii) follows immediately from partially differentiating (5.23) with respect to λ, taking $\overline{n}_{t+1}$ and $\underline{n}_{t+1}$ as given. □

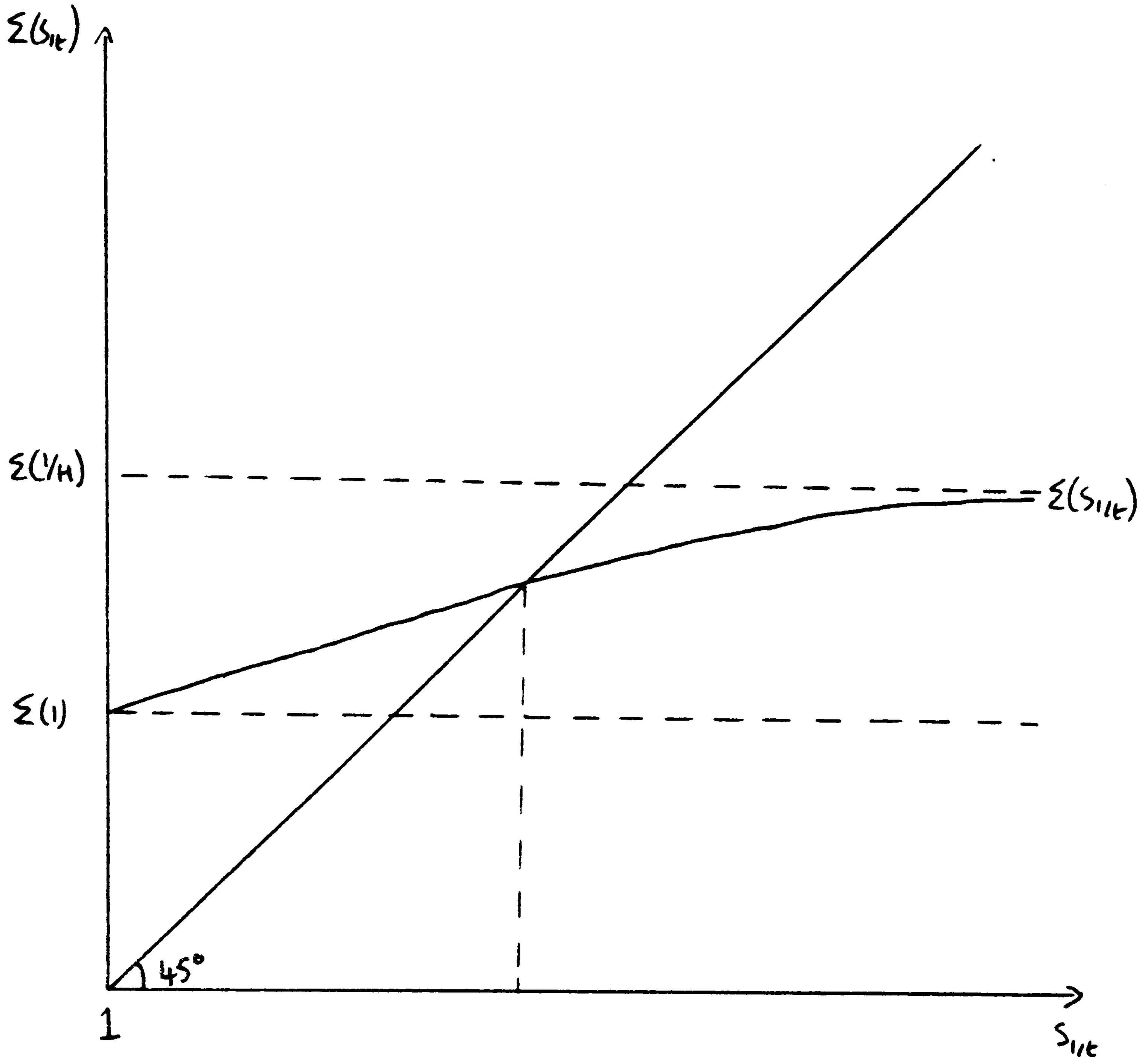


Figure 7: Existence of $\tilde{S}_{1,t}$.

where:
$$\Sigma(S_{1,t}) \equiv \left[\frac{\gamma^{v}\theta H}{\lambda(S_{1t})^{-1}(1+\rho)+\left(\lambda(S_{1t})^{-1}+H\right)\left(1+\mu\cdot H\right)}\right]^{\frac{1}{1-\sigma}}$$

Chapter 6

Endogenous Innovation, Static and Dynamic Comparative Advantage

6.1 Introduction

Throughout this thesis, it has been argued that the rate of technological change is an important determinant of an economy's long-run rate of growth. The present Chapter considers the relationship between technological change and international trade in a dynamic Ricardian model. For simplicity, we abstract from the distinction between *fundamental* and *secondary* innovation that has been the concern of the previous two Chapters, and return to the case where technological change is one-dimensional. The central argument of this Chapter is that an economy may face a *trade-off* between specialising in sectors in which it currently has a comparative advantage and specialising in those sectors in which it may acquire one in the future as a result of the potential for productivity improvement.

Under free trade, the pattern of production at each point in time in any one economy is determined by the pattern of comparative advantage. In any model of growth and trade, this pattern of comparative advantage is *endogenous*, and evolves over time in a way dependent upon relative rates of factor accumulation or technological change. In general, these relative rates of factor accumulation or technological change will themselves depend upon the pattern of specialisation, so that the pattern of specialisation feeds back to determine its own evolution over time. As will be argued below, this feedback generates the potential for it to be welfare improving to specialise in sectors in which one does not currently have a comparative advantage.

The present Chapter is concerned with two main questions. Firstly, under what circumstances is it optimal for an economy *not* to specialise according to its current pattern of comparative advantage ? Secondly, will the private sector resolve the trade-off between current and future patterns of comparative advantage optimally ? If it is optimal not to specialise according to current comparative advantage and the private sector does not correctly resolve the trade-off, then it becomes possible for free trade to be welfare *reducing* and protectionist measures to be welfare increasing. These questions are likely to be of particular concern to a *developing* economy, whose traditional comparative advantage may lie in low-technology sectors, but where the potential for productivity improvement in high-technology sectors may be large.

In any dynamic trade model, a distinction may be drawn between the traditional notion of comparative advantage used above (*static* comparative advantage (SCA)) and a second notion of *dynamic* comparative advantage (DCA). While SCA determines the pattern of specialisation at any one point in time, DCA is concerned with the evolution of patterns of specialisation over time. As such, Dynamic Comparative Advantage (DCA) is determined by rates of productivity growth in each sector in the two economies. The latter depend upon both the pattern of international specialisation and an economy's ability to reallocate resources over time in each sector, which we capture by means of the concept of *intertemporal* advantage (IA).

A number of authors have referred to DCA either in the context of models of endogenous growth and trade,[1] or in the context of the informal literature on the East Asian development experience.[2] However, the concept has remained ill-defined and its importance un-noted. Once suitably defined, the concept of dynamic comparative advantage (DCA) and the related notion of intertemporal advantage (IA) are central to the resolution of the two questions raised above. Furthermore, both concepts may be used to reinterpret a number of existing results in the endogenous growth literature.

The analysis begins in Section 2 with some empirical evidence from Korea and Central and Eastern Europe concerning the trade-off between current and future comparative advantage. Section 3 develops a simple Ricardian model of trade, which is extended to incorporate endogenous technological progress. In the present case, it less central to the analysis whether or not technological progress is the result of intentional investments. Hence, in the main body of the Chapter technological progress results from serendipitous learning by doing. Nonetheless,

---

[1] See for example Krugman (1987) and Grossman and Helpman (1991a). The earliest reference to dynamic comparative advantage of which I am aware is Nelson and Norman (1977).

[2] See for example Amsden (1989).

Appendix 1 extends the analysis to the case of profit-seeking Research and Development (R & D) and shows that all the results are robust to this extension.

Section 4 solves for equilibrium under autarky, and Section 5 for equilibrium under free trade. Section 6 explicitly defines the concepts of static and dynamic comparative advantage and the related notion of intertemporal advantage. Section 7 analyses the evolution of patterns of international trade over time, while Section 8 turns to the idea that there may be a trade-off between static and dynamic comparative advantage. Section 9 considers the welfare effects of international trade and Section 10 derives necessary and sufficient conditions for free trade to be welfare reducing. Section 11 examines the policy implications of this result, while Section 12 considers the relation of the present analysis to the existing literature. Finally, Section 13 concludes.

6.2 Empirical Relevance

A study by the World Bank in the 1960s "expressed the view that an integrated steel mill in Korea was a premature proposition without economic feasibility."[3] A number of factors suggested that steel making was an industry in which Korea was unlikely to have a comparative advantage.[4] Steel-making is highly capital intensive and subject to large economies of scale, yet capital was in relatively short supply and the Korean domestic market small. Furthermore,

---

[3] Pohang Iron and Steel Co. Ltd (1984), p. 23, cited in Amsden (1989).

[4] See for example Amsden (1989, Chapter 12), on which the first three paragraphs of this Section draw.

Korea was deficient both in one of the industry's main raw materials, iron ore, and in the skills necessary to manufacture steel. In addition, any Korean steel industry would face intense competition from nearby Japan, at that point in time, the world's most efficient steel producer.

Nonetheless, in 1973, the Korean government founded the Pohang Iron and Steel Company Ltd. (POSCO) with an initial investment of \$ 3.6bn. Government assistance in a wide variety of forms, including subsidisation of the cost of capital and investments in infrastructure have been central to POSCO's development. Nonetheless, the company soon became one of the lowest cost steel-producers in the world: in 1985, Korea unit costs of production were less than those of Japan and approximately 2/3 those in the United States.[5] Although there are problems in measuring profitability (especially given the existence of government subsidies), POSCO has shown a profit in every year since it was founded.[6] By 1988, POSCO had become the eleventh largest steel company in the world, operating 80 individual plants.

Although at the time POSCO was founded Korea did not appear to have a (static) comparative advantage in steel manufacture, it seems incontrovertible that it now does, and that the Korean government has played a central role in the achievement of this advantage. Of course, this does not prove that the establishment of the Korean steel industry was welfare increasing, or that investments in the steel industry have yielded strictly positive social returns. Nonetheless, it does suggest that the idea an economy might want to specialise in a sector in which it

---

[5] Source: Amsden (1989), Table 12.2, p. 298.

[6] Source: Enos and Park (1988), Table 7.16, p. 214.

does not initially have a (static) comparative advantage is of empirical relevance.

This idea seems to be even more applicable to the transition economies of Central and Eastern Europe. At present, real wages in these economies remain extremely low relative to those in the E.U. and to those in many Newly Industrialising Economies (N.I.E.s).[7] As a result, the current comparative advantage of these transition economies would appear to lie in unskilled labour intensive sectors, such as textiles and apparel. Nonetheless, a wide range of evidence suggests that a number of Central and East European Countries (C.E.E.C.s) have relatively high levels of general human capital.

Primary and secondary school enrolment ratios compare favourably with those in many industrialised economies, while educational attainment, as measured by average years of schooling, is almost identical to the O.E.C.D. average.[8] Furthermore, data from standardised science tests undertaken by the *International Association for the Evaluation of Educational Achievement* (I.E.A.) and cited by Wang and Winters (1994) suggest both Poland and especially Hungary are characterised by high levels of educational achievement relative to a number of industrialised economies.[9]

High levels of general human capital suggest that a number of C.E.E.C.s have the potential to acquire a (static) comparative advantage in skilled-labour or R & D intensive sectors. In general,

---

[7] For example, in 1992 hourly compensation costs in Hungary were $2.42 compared to a trade-weighted average for the E.U. of $19.92 and an average of $4.84 for the East Asian N.I.C.s. Source: Halpern (1995).

[8] This is partly due to a compulsory primary school system, which also ensures low adult illiteracy rates. Tertiary enrolment ratios compare less favourably with developed market economies.

[9] For example, Hungary's level of achievment at both "level 2" (14-15 year olds) and "level 3" (just before higher education) exceeds that in both Canada and Sweden.

production in these sectors requires not only general human capital but also the acquisition of specific skills and technological blueprints. However, one might expect the rate at which such specific skills or technological knowledge can be acquired to be positively correlated with the level of general human capital. If so, these economies have the potential to achieve rapid rates of productivity growth in skilled-labour or R & D intensive sectors. Thus, the question becomes: under what circumstances will it be optimal for the C.E.E.C.s to enter skilled-labour or R & D intensive sectors rather than specialising according to their current (static) comparative advantage in unskilled-labour intensive sectors ? Under what circumstances will the private sector ensure that such an outcome obtains ?

The analysis begins in the next Section by developing a dynamic Ricardian model of endogenous growth and international trade. In the following Section, we proceed to explicitly define concepts of *dynamic comparative advantage* and *intertemporal advantage*, which we argue hold the key to answering these questions.

6.3 A Dynamic Ricardian Model

In this Section we develop a simple model of international trade that follows Ricardo (1817), and is essentially a two-good version of Dornbusch *et al.* (1977). The basic model is then extended to incorporate bounded and unbounded learning by doing, while Appendix 1 considers the case of profit-seeking Research and Development (R & D). The analysis with intentional R & D is essentially the same as with learning by doing, and all this Chapter's results are robust to this extension.

Consider a world populated by two economies, "home" and "foreign," in which all foreign variables are denoted by an asterisk. Each economy may produce two final goods, a low-technology, traditional good z (e.g. agriculture, textiles) and a high-technology, frontier good y (e.g. industry, electronics). Both goods are produced with skilled labour, which is the sole primary factor of production. Home and foreign are populated with continua of representative consumers of mass $\bar{L}$ and $\bar{L}^*$ respectively. Time is continuous and is indexed by $\tau \geq 0$.

6.3.1 Consumer Preferences

Consumer preferences are identical in each of the two economies. The representative consumer is characterised by intertemporally additive separable preferences, with instantaneous utility defined over consumption of low-tech and high-tech goods,[10]

$$U_\tau = \int_\tau^\infty e^{-\rho(s-\tau)}.c_z^\beta c_y^{1-\beta} ds, \qquad 0 < \beta < 1, \tag{6.1}$$

Instantaneous utility is assumed to take the Cobb-Douglas form. For simplicity, we assume that there is no storage or savings technology, and hence at each point in time the representative consumer's expenditure equals her income. Each consumer is endowed with one unit of skilled labour, which is supplied inelastically with zero disutility.

---

[10] In general, throughout the following, we use lower case letters to denote per capita variables and upper case letters to denote aggregate magnitudes.

6.3.2 Production

The low- and high-technology goods are both produced with constant returns to scale technologies, which differ solely in terms of their productivities A_z and A_y. Home aggregate output of the low- and high-technology goods is thus given respectively by,

$$Z = A_z.L_z, \tag{6.2}$$

$$Y = A_y.L_y, \tag{6.3}$$

where L_z and L_y denote the quantities of skilled labour devoted to low- and high-technology goods manufacture respectively. Labour is assumed to be perfectly *mobile* within and perfectly *immobile* between economies. Hence, home labour market clearing requires,

$$L_z + L_y = \bar{L}, \tag{6.4}$$

Production in foreign is directly analogous, except that we allow productivity differences across economies. That is, A_z need not equal A_z^* and A_y need not equal A_y^*. Production of both the low- and high-technology goods is assumed to occur under conditions of perfect competition.

6.3.3 Learning by Doing

The production structure of the previous section is that of the standard textbook Ricardian model. However, following Krugman (1987), we assume that productivity in each sector i at a given point in time τ depends upon cumulative production experience $K_i(\tau)$,

$$A_z(\tau) = \psi_z . K_z(\tau), \tag{6.5}$$

$$A_y(\tau) = \psi_y . K_y(\tau), \tag{6.6}$$

where ψ_z and ψ_y are exogenous determinants of productivity in each sector such as climate, culture, political institutions and laws. Production experience accumulates as a result of *learning by doing*, which is assumed to be external to individual firms but specific to an industry and to an economy.[11] The particular specification for learning by doing chosen follows Parente (1994),

$$\dot{K}_z(\tau) = \begin{cases} \alpha_z - \gamma_z K_z(\tau) & \text{for} \quad z > 0 \\ 0 & \text{for} \quad z = 0 \end{cases}, \qquad \alpha_z, \gamma_z > 0, \tag{6.7}$$

$$\dot{K}_y(\tau) = \begin{cases} \alpha_y - \gamma_y K_y(\tau) & \text{for} \quad y > 0 \\ 0 & \text{for} \quad y = 0 \end{cases}, \qquad \alpha_y, \gamma_y > 0, \tag{6.8}$$

---

[11] That is, initially, we assume that there are no international spillovers of knowledge. However, as in Krugman (1987), it is straightforward to introduce such spillovers.

As the stock of cumulative production experience in a sector j (K_j) rises, the rate of learning by doing falls monotonically until cumulative production experience attains its upper bound $\bar{K}_j = \alpha_j/\gamma_j$, where $j = z, y$. Learning by doing is thus *bounded.* Sector-specific production experience is accumulated if output in a sector is positive. For simplicity, we assume that the rate of learning by doing is independent of the actual flow of output.[12] The foreign production and learning by doing technologies are directly analogous, except that the parameters α_z^*, α_y^*, γ_z^* and γ_y^* need not take the same values as in home.

In the present framework, bounded learning by doing implies that the economy's long-run rate of growth is zero.[13] In order to generate endogenous growth, we require either that the potential for learning by doing is unbounded or that (as in Appendix 1) profit-seeking Research and Development (R & D) is a source of technological progress. Unbounded learning by doing may be viewed as a special case of the above technology, where $\alpha_z = \alpha_z^* = 0$, $\gamma_z = -g_z$ and $\gamma_y = -g_y$,

$$\dot{K}_z(\tau) = \begin{cases} g_z K_z(\tau) & \text{for} \quad z > 0 \\ 0 & \text{for} \quad z = 0 \end{cases}, \qquad g_z > 0, \tag{6.9}$$

---

[12] The results that follow do not depend upon this assumption. The analysis could be generalised to allow the rate of learning by doing to depend upon the volume of output. However, this would only complicate the dynamics, without adding insight. Furthermore, Appendix 1 considers the case of profit-seeking R & D, where the rate of technological progress is a continuous choice variable.

[13] Chapter 4 considered the analysis of Young (1991), where learning by doing in each good is bounded, but where spillovers of learning by doing across goods generate the potential for unbounded growth.

$$\dot{K}_y(\tau) = \begin{cases} g_y K_y(\tau) & \text{for} \quad y > 0 \\ 0 & \text{for} \quad y = 0 \end{cases}, \qquad g_y > 0, \tag{6.10}$$

6.4 Autarkic Equilibrium

Since learning by doing is external to each firm, it remains consistent with the assumption of perfect competition. Autarkic Equilibrium may be illustrated with the standard tools of a Production Possibility Frontier (P.P.F.) and the indifference curves of the representative consumer. We solve for general equilibrium in home. However, the analysis remains exactly the same for foreign.

The Production Possibility Frontier (P.P.F.) is derived from (6.2), (6.3) and (6.4), and is illustrated in Figure 1. At each point in time,

$$\text{(PPF)} \qquad Y(\tau) = A_y(\tau).\bar{L} - \frac{A_y(\tau)}{A_z(\tau)}.Z(\tau), \tag{6.11}$$

In equilibrium, we require that the relative price of the low-tech good equals minus the Marginal Rate of Transformation between low- and high-tech goods. That is,

$$\frac{p_z(\tau)}{p_y(\tau)} = -MRT_{zy}(\tau) = -\frac{dY(\tau)}{dZ(\tau)} = \frac{A_y(\tau)}{A_z(\tau)} = \frac{\psi_y}{\psi_z}.\frac{K_y(\tau)}{K_z(\tau)}, \tag{6.12}$$

Consumer preferences are intertemporally additive separable, and, under the assumption of no storage or savings technology, income equals expenditure at each point in time τ. Consumers' sole decision problem concerns the allocation of instantaneous expenditure between low- and high-tech goods. In equilibrium, we require that the relative price of the low-tech good equals minus the Marginal Rate of Substitution between low- and high-tech goods. That is,

$$\frac{p_z(\tau)}{p_y(\tau)} = -MRS_{zy} = \frac{\partial u(c_z, c_y)/\partial c_z}{\partial u(c_z, c_y)/\partial c_y} = \frac{\beta}{1-\beta}.\frac{c_y(\tau)}{c_z(\tau)}, \tag{6.13}$$

With Cobb-Douglas instantaneous utility, the representative consumer's indifference curves take the form of a rectangular hyperbola, illustrated in Figure 1.

General equilibrium requires that both (6.12) and (6.13) be satisfied. Equilibrium is characterised by incomplete specialisation and is illustrated in Figure 1. As learning by doing occurs in each sector, the Production Possibility Frontier shifts outwards over time. Since instantaneous utility is Cobb-Douglas, the representative consumer allocates constant shares β and $(1-\beta)$ of her expenditure to low-tech and high-tech goods respectively. In equilibrium, the labour force $\bar{L}$ is allocated to the low-tech and high-tech sectors in the constant proportions β and $(1-\beta)$ respectively. Hence, $c_z(\tau) = z(\tau) = A_z(\tau).\beta\bar{L}$ and $c_y(\tau) = y(\tau) = A_y(\tau).(1-\beta)\bar{L}$.

If learning by doing is unbounded, endogenous growth occurs in both the low- and high-tech sectors. The rate of growth of instantaneous utility is then a weighted average of productivity growth rates in the two sectors. In contrast, if learning by doing is bounded, output in each sector converges to the analogue of a Solow steady-state. Hence, the rate of growth of instantaneous utility falls over time.

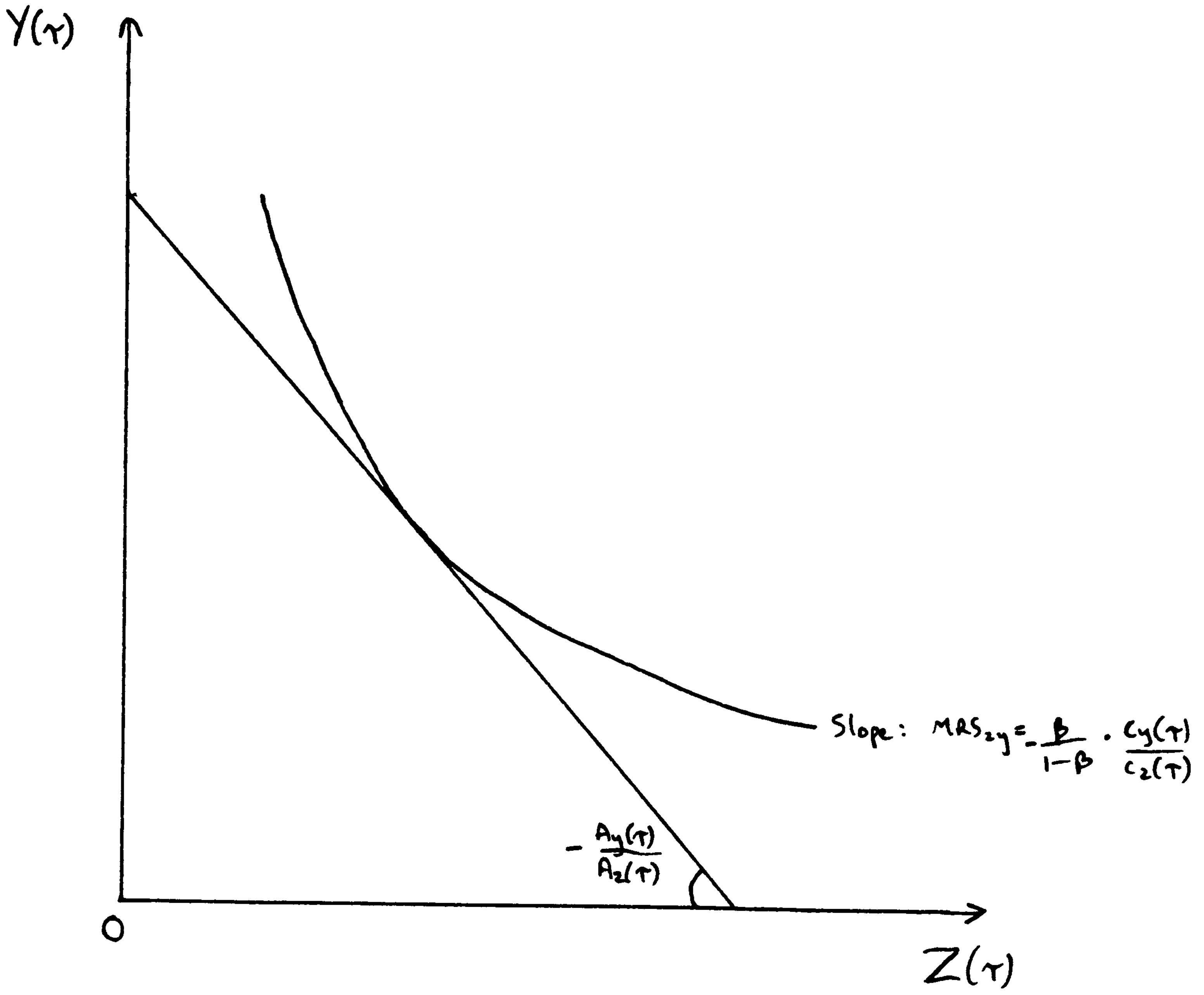


Figure 1: Autarkic Equilibrium in the Dynamic Ricardian Model.

6.5 Free Trade Equilibrium

Consider the opening of trade between the two economies at some time $\tau = \tau_1 > 0$. With free trade and zero transport costs, the price of the low-tech and high-tech goods must be the same in each economy. Given the constant returns to scale technologies (6.2) and (6.3), at least one economy must specialise in the free trade equilibrium.[14] The ensuing exposition follows that of the standard Ricardian model in Krugman and Obstfeld (1994).

Consumers' sole decision problem remains the allocation of expenditure between low- and high-tech goods at each point in time τ. Preferences are identical in the two economies, and, with Cobb-Douglas instantaneous utility, world demand for the low-tech good *relative* to the high-tech is simply,

$$RD_z(\tau) \equiv \frac{C_z^W(\tau)}{C_y^W(\tau)} = \frac{C_z(\tau) + C_z^*(\tau)}{C_y(\tau) + C_y^*(\tau)} = \frac{\beta}{(1-\beta)} . \frac{p_y(\tau)}{p_z(\tau)}, \tag{6.14}$$

Production in home may be characterised by either complete or incomplete specialisation. Perfect competition implies that the wage in the low- and high-tech sectors is given respectively by,

$$w_z(\tau) = A_z(\tau).p_z(\tau) \qquad \text{and} \qquad w_y(\tau) = A_y(\tau).p_y(\tau), \tag{6.15}$$

---

[14] Incomplete specialisation in both economies can only occur in free trade equilibrium if the two economies are identical.

In the case of complete specialisation, the wage may differ across the two sectors. Home will specialise in low-tech production at time τ if and only if $w_z(\tau) > w_y(\tau)$, which requires,

$$\frac{p_z(\tau)}{p_y(\tau)} > \frac{A_y(\tau)}{A_z(\tau)} = \frac{\psi_y}{\psi_z}.\frac{K_y(\tau)}{K_z(\tau)}, \tag{6.16}$$

Similarly, foreign will specialise in high-tech production at time τ if and only if $w_y^*(\tau) > w_z^*(\tau)$, which requires,

$$\frac{A_y^*(\tau)}{A_z^*(\tau)} = \frac{\psi_y^*}{\psi_z^*}.\frac{K_y^*(\tau)}{K_z^*(\tau)} > \frac{p_z(\tau)}{p_y(\tau)}, \tag{6.17}$$

In one of the two economies, specialisation may be incomplete. In this case, we require that the wage in the two sectors is equalised. Hence, either (6.16) or (6.17) will hold with equality. Together, (6.16) and (6.17) define the world supply of the low-tech good *relative* to that of the high-tech good, $RS_z(\tau) = \frac{Z(\tau)+Z^*(\tau)}{Y(\tau)+Y^*(\tau)}$. General equilibrium requires that relative demand equal relative supply. Figure 2 illustrates free trade equilibrium in the case of complete specialisation in both economies.

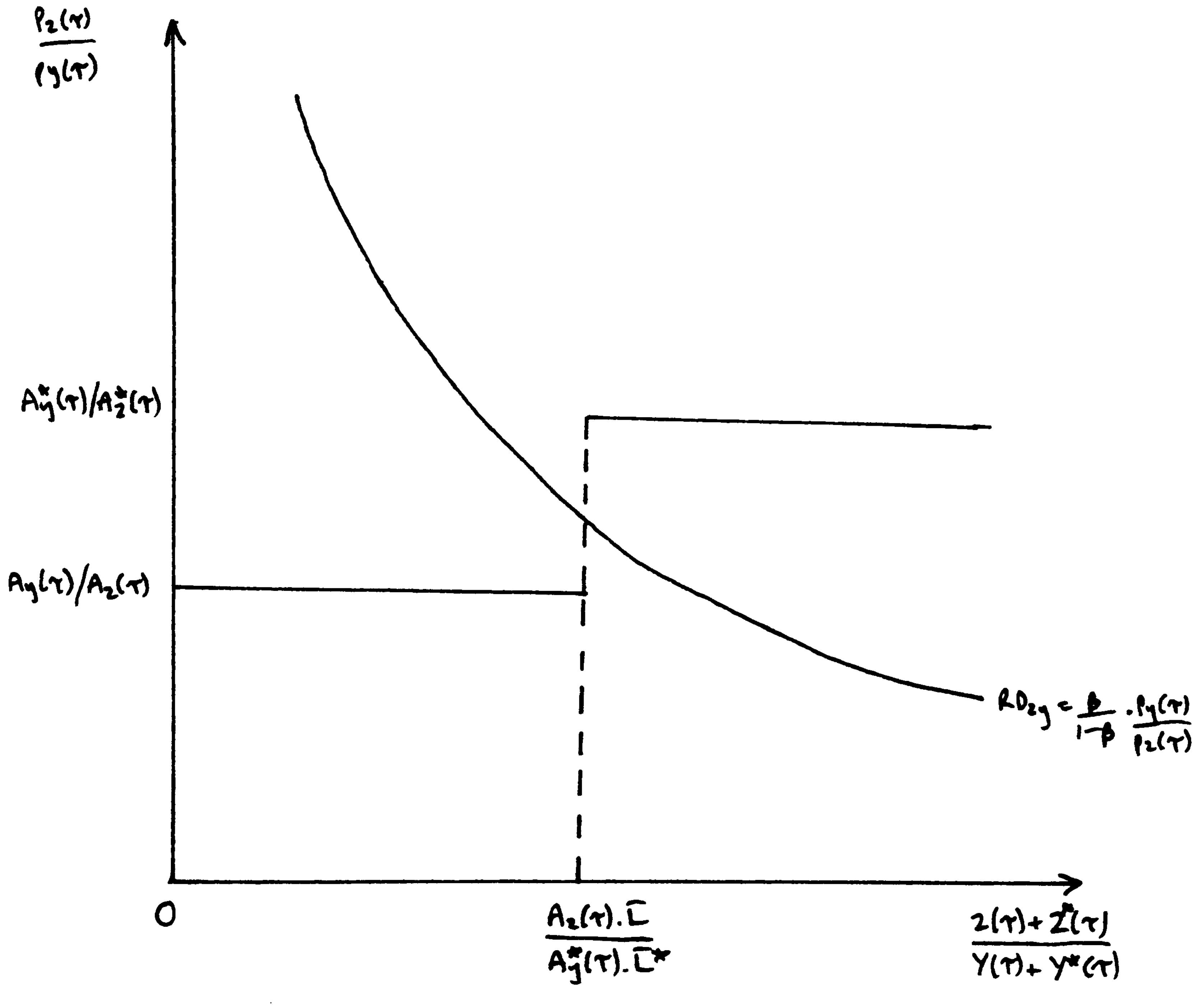


Figure 2: Free Trade Equilibrium.

6.6 Static and Dynamic Comparative Advantage

6.6.1 Static Comparative Advantage

The pattern of specialisation at any point in time τ is determined by the traditional or Ricardian notion of comparative advantage, which we term *static* comparative advantage,[15]

Definition 1 Static Comparative Advantage: *An economy has a static comparative advantage in the production of a good at time τ if the opportunity cost of producing the good at home at time τ is lower than in the other economy.*

From definition 1, home has static comparative advantage in *low*-tech production at time τ if and only if,

$$\frac{A_y(\tau)}{A_z(\tau)} < \frac{A_y^*(\tau)}{A_z^*(\tau)}, \tag{6.18}$$

$$\Leftrightarrow \quad \frac{\psi_y}{\psi_z}.\frac{K_y(\tau)}{K_z(\tau)} < \frac{\psi_y^*}{\psi_z^*}.\frac{K_y^*(\tau)}{K_z^*(\tau)},$$

From (6.16) and (6.17), this is also the condition for home to specialise (either completely or incompletely) in low-tech production in the free trade equilibrium.

From (6.18), the pattern of static comparative advantage at any point in time τ is determined partly by *exogenous* factors such as climate, political institutions and laws, which are

---

[15] The ensuing definition follows the definition of Ricardian comparative advantage in Södersten and Reed (1994), p. 6.

manifested in the values of ψ_j ($j = y, z$) for home and foreign. These determine how productive an economy is in each sector for a given level of production experience. However, static comparative advantage also depends upon the stocks of sector-specific production experience in home and foreign at time τ. The latter are *endogenously* determined. The stock of cumulative production experience in a sector j at a given point in time τ depends partly upon *history* (in the form of the initial stocks of production experience $K_j(0)$ and $K_j^*(0)$, for $j = z, y$) and partly upon the *cumulative effects of learning by doing* or (in the model of Appendix 1) *cumulative research effort.* Sector-specific production experience in each economy (and hence the pattern of static comparative advantage) evolves *endogenously* over time, as determined by either rates of learning by doing or profit-seeking investments in Research and Development (R & D).

6.6.2 Dynamic Comparative Advantage

While static comparative advantage determines the pattern of specialisation at any one point in time, the *evolution* of the pattern of specialisation over time is determined by *dynamic* comparative advantage.

Definition 2 Dynamic Comparative Advantage: *An economy has a dynamic comparative advantage in the production of a good at time τ if the rate of growth of the opportunity cost of producing the good at time τ is lower than in the other economy.*

In terms of the model of the previous Section, home will have a dynamic comparative advantage in *high*-tech production if and only if,

$$\frac{\partial\left(A_z(\tau)/A_y(\tau)\right)/\partial\tau}{A_z(\tau)/A_y(\tau)} < \frac{\partial\left(A_z^*(\tau)/A_y^*(\tau)\right)/\partial\tau}{A_z^*(\tau)/A_y^*(\tau)}, \tag{6.19}$$

which requires,

$$\left(\frac{\dot{A}_z(\tau)}{A_z(\tau)} - \frac{\dot{A}_y(\tau)}{A_y(\tau)}\right) < \left(\frac{\dot{A}_z^*(\tau)}{A_z^*(\tau)} - \frac{\dot{A}_y^*(\tau)}{A_y^*(\tau)}\right), \tag{6.20}$$

If home has a dynamic comparative advantage in the *high*-tech sector, then it follows immediately that *foreign* must have a dynamic comparative advantage in the *low*-tech sector.

The concept of dynamic comparative advantage is implicit in the discussion in several models of endogenous growth and trade (see for example Matsuyama (1992) and Grossman and Helpman (1991a)). The objective of the present analysis is to make this concept explicit, and to show that, as defined above, dynamic comparative advantage yields considerable insight into the evolution of patterns of international specialisation and the welfare effects of trade.

6.6.3 Intertemporal Advantage

From equation (6.20), the pattern of dynamic comparative at any one point in time is determined by rates of productivity growth in each sector of the two economies. The specification of learning by doing in equations (6.7) and (6.8) implies that the latter depend upon both the parameters of the learning technology (α_j and γ_j for $j = z, y$) and the pattern of international specialisation. Thus, the rate of learning by doing is zero if output in a sector is not strictly positive.

More generally, as in the model of Research and Development (R & D) in Appendix 1, the rate of technological progress in a sector will be the result of intentional investments by profit-seeking agents. In this case, the pattern of dynamic comparative advantage will be determined by the productivity of these investments and the pattern of international specialisation.[16] In each case, dynamic comparative advantage depends upon the nature of international specialisation and an economy's ability to reallocate resources over time in each sector. The latter we capture by means of the concept of *intertemporal* advantage,

Definition 3 Intertemporal Advantage: *An economy has an intertemporal advantage in the production of a good at time τ if the opportunity cost of raising productivity in that sector at home at time τ is lower than in the other economy.*

With learning by doing, productivity growth is a positive externality of current production, and the social opportunity cost of raising productivity is negative. In this case, intertemporal advantage corresponds to the rate at which current production will raise future productivity through serendipitous learning by doing. If learning by doing is *bounded*, intertemporal advantage depends upon both the parameters of the learning technology (α_j and γ_j) and the sector-specific stock of cumulative production experience K_j, for $j = z, y$. From (6.7) and (6.8), for $z(\tau) > 0$ and $y(\tau) > 0$,

---

[16] In the model of Appendix 1, it is again the case that the rate of technological change in a sector is zero if output is not strictly positive.

$$\frac{\dot{A}_z(\tau)}{A_z(\tau)} = \frac{\dot{K}_z(\tau)}{K_z(\tau)} = \frac{\alpha_z}{K_z(\tau)} - \gamma_z, \tag{6.21}$$

$$\frac{\dot{A}_y(\tau)}{A_y(\tau)} = \frac{\dot{K}_y(\tau)}{K_y(\tau)} = \frac{\alpha_y}{K_y(\tau)} - \gamma_y, \tag{6.22}$$

With *unbounded* learning by doing, intertemporal advantage depends solely upon the parameters of the learning technology, g_z and g_y.[17]

While static and dynamic comparative advantage are concerned with the relative opportunity cost of production in different *sectors* in the two economies, intertemporal advantage is concerned with the relative opportunity cost of production *today* versus production *tomorrow*. As a result, it is possible for an economy to have an intertemporal advantage in *both* of the two production sectors (indeed, this will typically be the case if both production sectors have the same accumulation technology).

6.6.4 The Interaction Between Static and Dynamic Comparative Advantage

From equation (6.20), the pattern of *intertemporal advantage* (IA) is clearly an important determinant of whether or not an economy has a *dynamic comparative advantage* (DCA) in a sector. However, in both the learning by doing specification and the model of profit-seeking Research and Development (R & D), dynamic comparative advantage (DCA) also depends

---

[17] Since in this case, $\dot{A}_z(\tau)/A_z(\tau) = g_z$ and $\dot{A}_y(\tau)/A_y(\tau) = g_y$.

upon the nature of international specialisation and hence upon an economy's current pattern of *static comparative advantage* (SCA).

Static comparative advantage (SCA) determines international specialisation at a given point in time. The nature of international specialisation, together with the pattern of intertemporal advantage (IA), then determines rates of productivity growth in each sector and an economy's pattern of dynamic comparative advantage (DCA). At the same time, patterns of DCA determine the evolution of SCA and international specialisation over time. Thus, the *endogeneity* of rates of productivity growth means that static comparative advantage (SCA) *feeds back* to determine its own evolution over time.

Furthermore, since dynamic comparative advantage (DCA) depends on the nature of international specialisation, a distinction emerges between an economy's *actual* pattern of DCA and the *potential* pattern it might achieve, were international specialisation to be different. Thus, an economy might have an intertemporal advantage in a sector (IA) and a *potential* DCA, but this potential will not be translated into an actual DCA if the current pattern of static comparative advantage (SCA) leads it to specialise in another sector.

In a similar way, the fact that static comparative advantage (SCA) is endogenous, and evolves over time in a way determined by dynamic comparative advantage (DCA), means that the *actual* pattern of SCA at one point in time may differ quite considerably from the *potential* pattern that might be achieved at a future point in time. Both distinctions between *actual* and *potential* comparative advantage will be important in the analyses of economic welfare and public policy that follow. However, we begin in the next Section by considering the evolution of patterns of international specialisation over time.

6.7 Trade Dynamics

In the present model, the evolution of patterns of international trade depends crucially upon whether specialisation in an economy is *complete* or *incomplete*. Suppose specialisation is *complete*, and home specialises in the low-tech sector and foreign in high-tech,

$$\frac{A_y^*(\tau)}{A_z^*(\tau)} > \frac{p_z(\tau)}{p_y(\tau)} > \frac{A_y(\tau)}{A_z(\tau)}, \tag{6.23}$$

Learning by doing only occurs if output in a sector is positive. Hence, as long as home's potential for learning in the low-tech sector and foreign's potential for learning in the high-tech sector have not been exhausted ($K_z < \alpha_z/\gamma_z$ and $K_y^* < \alpha_y^*/\gamma_y^*$), it follows immediately from equation (6.20) that *home* must have a dynamic comparative advantage in the *low*-tech sector and foreign must have such an advantage in the high-tech sector. Each economy has an actual *dynamic* comparative advantage in the same sector as which it has a *static* comparative advantage. $A_z(\tau)$ and $A_y^*(\tau)$ rise over time, while $A_y(\tau)$ and $A_z^*(\tau)$ remain constant. Thus, as in Krugman (1987), the initial pattern of static comparative advantage is *reinforced* over time. Figure 3 illustrates the evolution of static comparative advantage between two points in time

τ_1 and $\tau_2 > \tau_1$.

If specialisation is *incomplete*, then the initial pattern of static comparative advantage may be either *reinforced* or *reduced* over time. Suppose foreign specialises in the high-tech sector while specialisation at home is incomplete,

$$\frac{A_y^*(\tau)}{A_z^*(\tau)} > \frac{p_z(\tau)}{p_y(\tau)} = \frac{A_y(\tau)}{A_z(\tau)}, \tag{6.24}$$

As long as there remains potential for learning by doing in the sectors where output is positive, home will enjoy productivity growth in both the low-tech and high-tech sectors, while foreign will experience productivity growth in the high-tech sector: $\dot{A}_y/A_y > 0$, $\dot{A}_z/A_z > 0$, $\dot{A}_y^*/A_y^* > 0$ and $\dot{A}_z^*/A_z^* = 0$. From equation (6.20), home may have an actual dynamic comparative advantage in *either* the low-tech *or* the high-tech sectors, depending upon relative rates of learning by doing in the two economies. If home has an actual *dynamic* comparative advantage in the sector in which it has a *static* comparative *dis*advantage (the *high*-tech sector in the example above), then the initial pattern of static comparative advantage will be *reduced* over time. If home's dynamic comparative advantage is sufficiently large and persistent, then the initial pattern of static comparative advantage will be *reversed*, as shown in Figure 4.

In both the case of sector-specific learning by doing and the model of profit-seeking Research and Development (R & D) in the Appendix, productivity growth is dependent upon output in a sector being positive. As a result, an economy can only achieve productivity growth in sectors

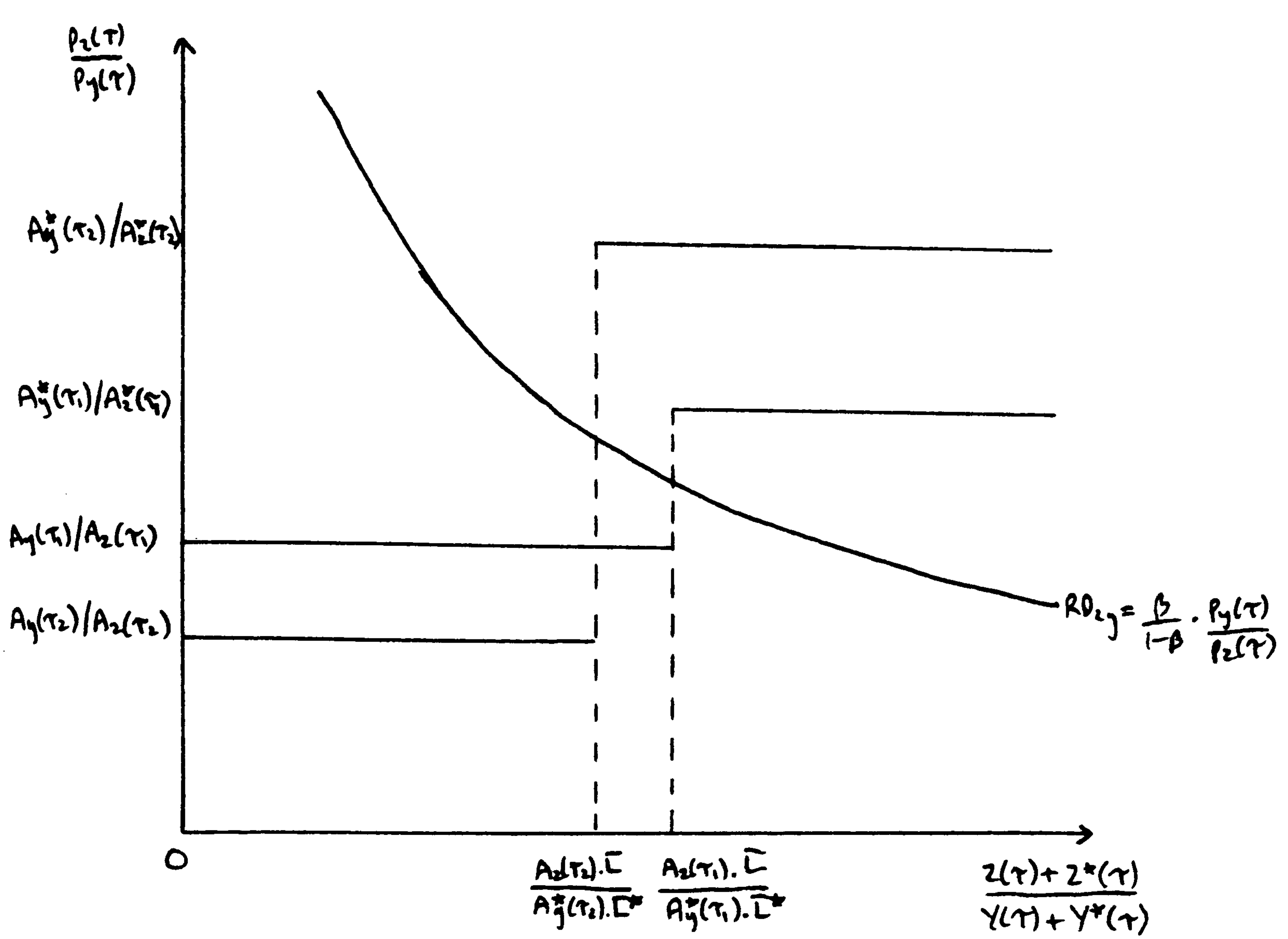


Figure 3: The Evolution of SCA over time under complete specialisation, $\tau_2 > \tau_1$.

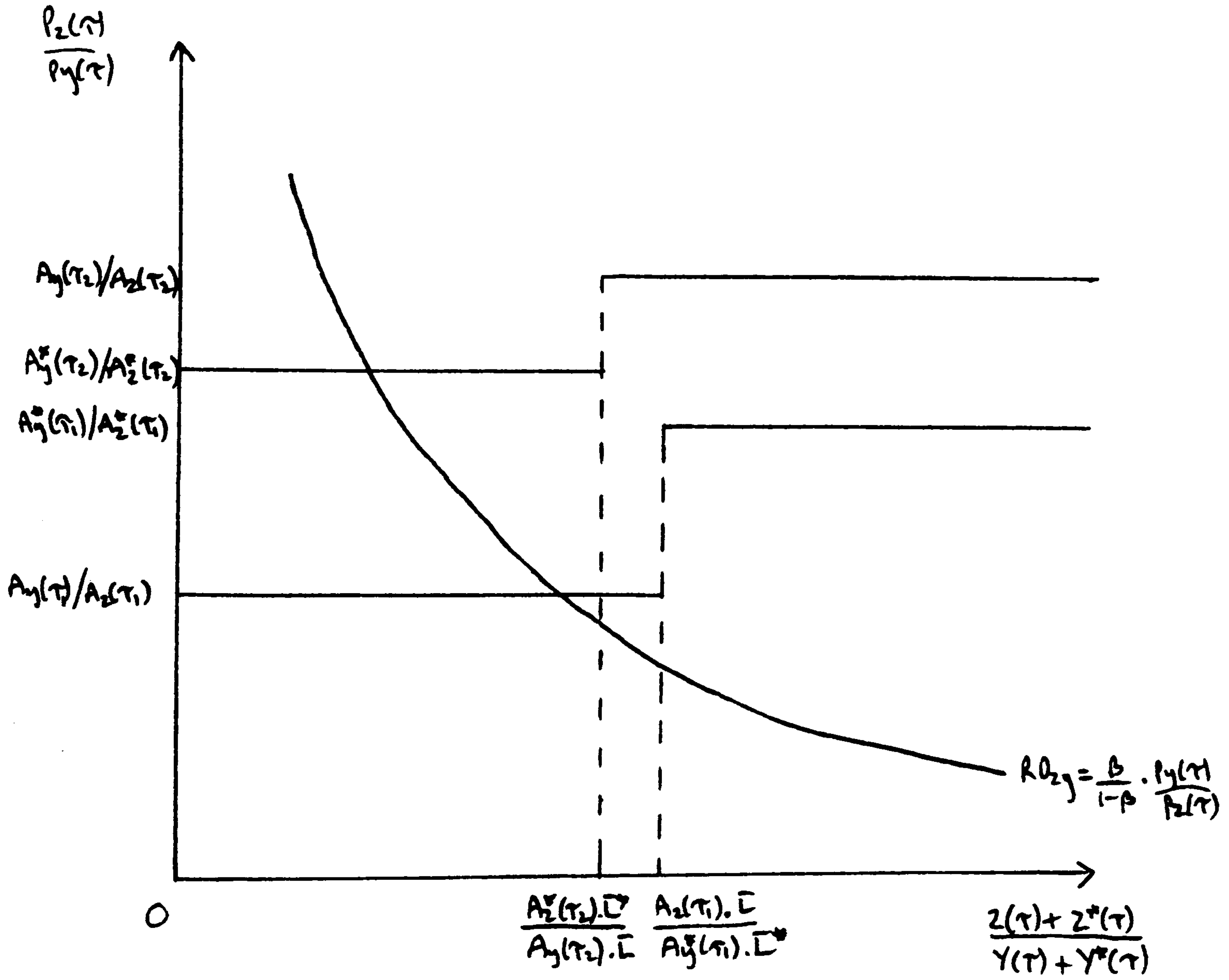


Figure 4: The Evolution of SCA over time under incomplete specialisation, $\tau_2 > \tau_1$.

in which it has an initial static comparative *dis*advantage if specialisation is *incomplete.* Hence, the reversal of static comparative advantage is dependent upon specialisation being incomplete.

Incomplete specialisation is not an implausible outcome. Furthermore, even if specialisation is *complete*, the initial pattern of static comparative advantage may still be reduced if there are *spillovers* of learning by doing across sectors. The analysis of Young (1991) (reviewed in Chapter 4) may be interpreted in these terms. In Young (1991), learning by doing is assumed to take the form of an economy-wide externality over all goods for which the potential for learning has not yet been exhausted. Each economy may produce a continuum of goods and specialisation is necessarily complete. Nonetheless, spillovers of learning by doing mean that a sufficiently large rate of learning by doing in a backward economy may induce a reversal of the initial pattern of (static) comparative advantage. In the context of the present analysis, Young's result may be explained in terms of the backward economy having an actual *dynamic* comparative advantage in those goods in which it initially has a static comparative *dis*advantage.

6.8 The Trade-off Between Static and Dynamic Comparative Advantage

In the analysis above, the nature of international specialisation at any one point in time τ is determined by the pattern of *static* comparative advantage. This pattern of static comparative advantage may be either *reinforced* or *reduced* over time depending upon the actual pattern of dynamic comparative advantage. However, because rates of productivity growth depend partly on the nature of international specialisation, it was argued above that a distinction exists between *actual* and *potential* patterns of *dynamic* comparative advantage. Static comparative advantage may lead an economy to specialise in one sector, even though it has an intertemporal advantage and a *potential* dynamic comparative advantage in another. Furthermore, this potential dynamic comparative advantage might be sufficiently large as to be able to reverse the initial pattern of static comparative advantage, so that *current* and *future potential* patterns of *static* comparative advantage differ.

This immediately leads to the two questions raised in the introduction. Firstly, could ever be optimal *not* to specialise according to the *current* pattern of static comparative advantage, and instead specialise in sectors in which one can attain a static comparative advantage in the *future* as a result of the potential pattern of *dynamic* comparative advantage ? Secondly, under what circumstances will private sector agents correctly resolve the trade-off between *current* and *future* patterns of static comparative advantage (or between current static comparative advantage and potential dynamic comparative advantage) ?

In the present framework, productivity growth may be the result of either serendipitous learning by doing or profit-seeking Research and Development (R & D). In both cases, technological change is characterised by what Aghion and Howitt (1992) term an *intertemporal spillover.* In the learning by doing case, the knowledge acquired each period builds upon the economy's existing stock of sector-specific cumulative production experience. In the model of profit-seeking R & D of Appendix 1, each researcher is concerned with the flow of profits to be derived from innovation over the finite period over which a patent applies. However, each innovation augments the stock of technological knowledge in a given sector, upon which future generations of researchers may build. Research "stands upon the shoulders" of previous discoveries, and a welfare maximising social planner would wish to take this intertemporal spillover into account.

Since learning by doing is a pure externality of current production, the pattern of international specialisation ay any one point in time is determined solely by *static* comparative advantage (SCA). In a similar way, the intertemporal spillover characterising the research process in Appendix 1 means that each generation of researchers is only concerned with the flow of profits from research success in the current period. Hence, the pattern of international specialisation at any one point in time is again determined by *static* comparative advantage (SCA).

In both cases, private sector agents to do not internalise the potential for future productivity improvement.[18] Hence, if it is welfare improving for an economy to specialise in sectors in which it does *not* have a static comparative advantage but exhibits a potential *dynamic* comparative advantage, then government intervention will be required. Furthermore, we show below that free trade, because it induces specialisation according to the current pattern of static comparative

---

[18] Redding (1996c) considers the case where private sector agents do fully internalise the potential for productivity improvement in the context of the infant-industry argument.

advantage, *may* (in certain circumstances) be *welfare reducing* relative to autarky.

6.9 Static and Dynamic Effects of Trade

In models of endogenous growth and trade, the standard *static* or "once-off" gains from trade are augmented with *dynamic* or "continuing" effects upon intertemporal welfare (see for example Grossman and Helpman (1991a), Rivera-Batiz and Romer (1991a), (1991b) and Taylor (1994)). While the static *gains* from trade refer to the once-off increase in the *level* of consumption and output induced by specialisation according to static comparative advantage, the dynamic effects are concerned with the impact of trade on intertemporal welfare through the economy's rate of long-run *growth*.

Thus, suppose that at some time $\tau = \tau_1 > 0$, two previously autarkic economies (home and foreign) have the choice of whether to engage in free trade from time τ_1 onwards (regime F) or whether to remain autarkic (regime N, "no trade").

6.9.1 Static Gains From Trade

Home is assumed to have an initial *static* comparative advantage in the low-tech sector. To begin with, we restrict consideration to equilibria characterised by *complete* specialisation in home. One unit of skilled labour produces $A_y^F(\tau)$ units of the high-tech good at home, while, by specialising in the low-tech sector and trading, home obtains $A_z^F(\tau).p_z^F(\tau)/p_y^F(\tau)$ units of the high-tech good. Free trade will raise instantaneous welfare if and only if,

$$A_z^F(\tau).\frac{p_z^F(\tau)}{p_y^F(\tau)} > A_y^F(\tau), \tag{6.25}$$

This inequality must be satisfied at time τ_1, since it is exactly the same condition for home to specialise in the low-tech sector (see equation (6.16)). For all $\tau \geq \tau_1$ for which (6.25) holds, instantaneous gains from trade will occur as a result of the exploitation of static comparative advantage. These constitute the standard "*static*" gains from trade and are illustrated in Figure 5, where the Consumption Possibility Frontier (C.P.F.) available through trade lies strictly outside the Production Possibility Frontier (P.P.F.) at each point in time τ.

6.9.2 Dynamic Gains and Losses From Trade

Specialisation in free trade equilibrium is assumed to be *complete* in home. Home specialises in the low-tech sector, and will accumulate (sector-specific) production experience as learning by doing occurs. Low-tech goods productivity $A_z^F(\tau)$ will rise over time, and this is illustrated in Figure 5 by an outward shift in the P.P.F. around its intersection with the z-axis between the points in time τ_1 and $\tau_2 > \tau_1$. Cumulative production experience in the home high-tech sector will remain unchanged, and hence $A_y^F(\tau) = A_y^F(\tau_1)$ for all $\tau \geq \tau_1$.

In contrast, were home to remain autarkic from time τ_1 onwards, specialisation would be *incomplete* and learning by doing would proceed in both the low-tech *and* high-tech sectors. Under autarky, both low-tech and high-tech goods productivity $A_z^N(\tau)$ and $A_y^N(\tau)$ will rise over time, and the Production Possibility Frontier (P.P.F.) will shift outwards over time. The latter

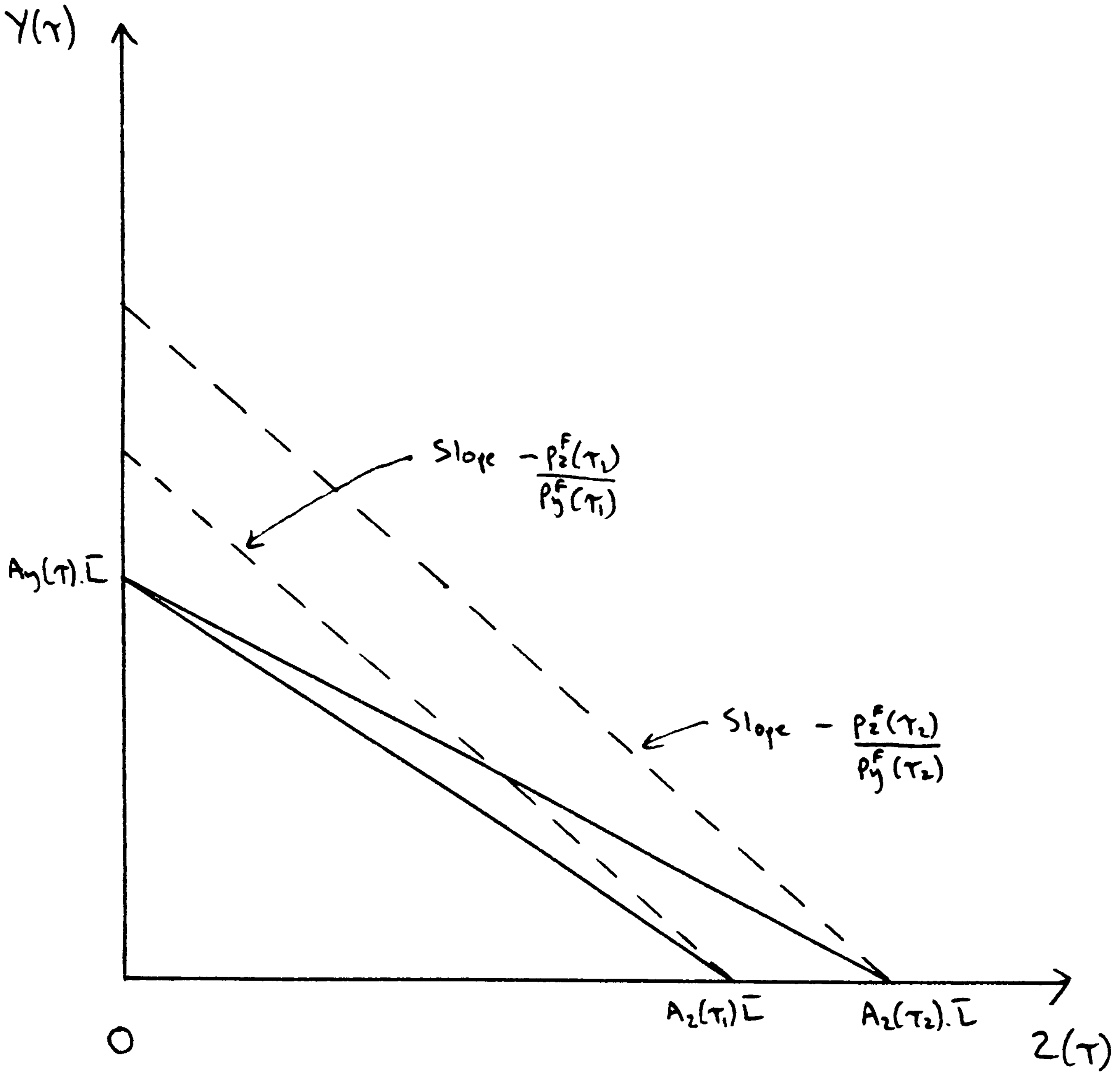


Figure 5: Static Gains from Trade, where $\tau_2 > \tau_1$

——— Production Possibility Frontier (P.P.F.)

- - - Consumption Possibility Frontier (C.P.F.)

may also exhibit a change in its slope, depending upon relative rates of learning by doing in the two sectors.

By trading with foreign at time τ_1, home forgoes its own potential to achieve productivity growth in the high-tech sector. If home's potential rate of productivity growth under autarky exceeds foreign's actual rate of productivity growth under free trade, this constitutes a "*dynamic loss*" from trade. If home's potential rate of productivity growth under autarky falls short of foreign's actual rate of productivity growth under free trade, this constitutes a "*dynamic gain*" from trade.

If there are dynamic losses from free trade, then it is conceivable that, at some time $\tau_2 > \tau_1$, the Production Possibility Frontier (P.P.F.) achieved under autarky will lie outside the Consumption Possibility Frontier (C.P.F.) that would be achieved by this time under free trade. Such an eventuality is illustrated in Figure 6, and *instantaneous* welfare at time τ_2 under free trade will be lower than it would have been under autarky.

6.10 The Welfare Implications of Trade

In this Section, we show that, if there are dynamic losses from trade, they may outweigh the static gains. International trade, by inducing an economy to specialise in sectors in which it currently has a *static* comparative advantage *may* reduce the intertemporal welfare of a representative agent. A central feature of the present analysis is that it is possible to derive *necessary* and *sufficient* conditions for free trade to be welfare reducing, and to relate these conditions to

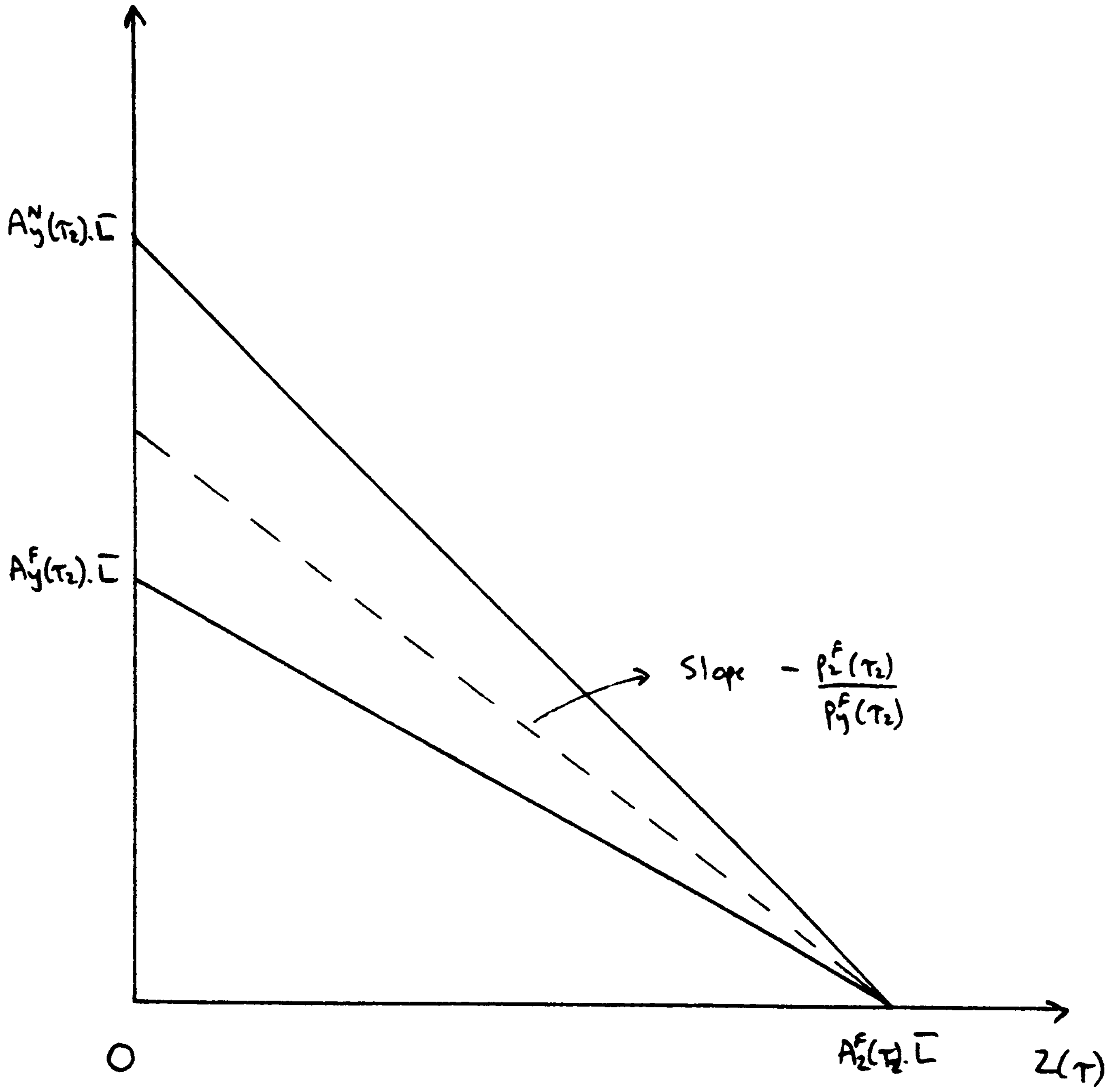


Figure 6: Instantaneous Welfare Under Free Trade may be lower at time $\tau_2 > \tau_1$ than it would have been under Autarky.

the concepts of *dynamic comparative advantage* and *intertemporal advantage* introduced above. In order to keep things as tractable as possible, the ensuing analysis will be undertaken for the case of *unbounded* learning by doing.[19]

6.10.1 Welfare Under Autarky

Suppose that the home economy chooses to remain autarkic for all $\tau \geq \tau_1$. The representative agent's income is equal to the wage in the production sector, which under autarky is given by $w(\tau) = p_z^N(\tau).A_z^N(\tau) = p_y^N(\tau).A_y^N(\tau)$ for all $\tau \geq \tau_1$. Instantaneous utility is Cobb-Douglas. Hence, in equilibrium, the representative agent allocates her income to expenditure on low-tech and high-tech goods in the constant proportions β and $(1-\beta)$ respectively. Equilibrium autarkic consumption of low-tech and high-tech goods is thus,

$$c_z^N(\tau) = \beta.A_z^N(\tau), \qquad c_y^N(\tau) = (1-\beta).A_y^N(\tau), \qquad \text{for all } \tau \geq \tau_1,$$

From (6.1), it follows that the representative agent's intertemporal utility is given by,

$$U_{\tau_1}^N = \int_{\tau_1}^{\infty} e^{-\rho(\tau-\tau_1)}.\left[\beta.A_z^N(\tau)\right]^{\beta}.\left[(1-\beta).A_y^N(\tau)\right]^{1-\beta} d\tau, \tag{6.26}$$

Under autarky, specialisation is incomplete and home experiences learning by doing in both the low-tech and high-tech sectors. With unbounded learning by doing, $A_z^N(\tau) = e^{g_z(\tau-\tau_1)}.A_z(\tau_1)$

---

[19] The analysis with profit-seeking Research and Development (R & D) is directly analogous. With *bounded* learning by doing, the analysis must be modified to take into account the fact that patterns of dynamic and intertemporal advantage change over time.

and $A_y^N(\tau) = e^{g_y(\tau-\tau_1)}.A_y(\tau_1)$ for all $\tau \geq \tau_1$. Substituting for $A_z^N(\tau)$ and $A_y^N(\tau)$ in (6.26) and evaluating the integral, we obtain the following expression for autarkic intertemporal welfare,

$$U_{\tau_1}^N = \frac{\beta^\beta(1-\beta)^{1-\beta}.[A_z(\tau_1)]^\beta.[A_y(\tau_1)]^{1-\beta}}{\rho - \beta g_z - (1-\beta)g_y}, \tag{6.27}$$

6.10.2 Welfare Under Free Trade

In contrast, suppose that home chooses to trade with foreign for all $\tau \geq \tau_1$. Specialisation in home is assumed to be complete. Hence, given the initial pattern of static comparative advantage, home specialises in the low-tech sector. The representative agent's income is given by the wage in the low-tech sector: $w(\tau) = p_z^F(\tau).A_z^F(\tau)$ for all $\tau \geq \tau_1$. Since instantaneous utility is Cobb-Douglas, it follows that free trade consumption of the low-tech and high-tech goods is equal to,

$$c_z^F(\tau) = \beta.A_z^F(\tau), \qquad c_y^F(\tau) = \frac{(1-\beta).p_z^F(\tau).A_z^F(\tau)}{p_y^F(\tau)}, \qquad \text{for all } \tau \geq \tau_1, \tag{6.28}$$

From (6.1), the representative agent's intertemporal utility is thus,

$$U_{\tau_1}^F = \int_{\tau_1}^{\infty} e^{-\rho(\tau-\tau_1)}.\left[\beta.A_z^F(\tau)\right]^\beta.\left[(1-\beta).A_z^F(\tau).\frac{p_z^F(\tau)}{p_y^F(\tau)}\right]^{1-\beta} d\tau, \tag{6.29}$$

Since specialisation in home is complete, home only experiences learning by doing in the low-tech sector. With unbounded learning by doing, $A_z^F(\tau) = e^{g_z(\tau-\tau_1)}.A_z(\tau_1)$ and $A_y^N(\tau) = A_y(\tau_1)$

for all $\tau \geq \tau_1$. Equation (6.29) implies that, in order to solve explicitly for intertemporal welfare, we require an expression for free trade relative prices. The latter will depend upon whether specialisation in foreign is complete or incomplete.

Free Trade Relative Prices

By assumption, home has an initial *static* comparative advantage in the low-tech sector. If specialisation is *complete* in both economies, home will produce low-tech goods and foreign high-tech goods. The relative supply of the low-tech good will equal $\frac{A_z^F(\tau)\bar{L}}{A_y^{F*}(\tau)\bar{L}^*}$ for all $\tau \geq \tau_1$.[20] Relative demand is determined according to (6.14), and the free trade equilibrium price of the low-tech good is thus,

$$\frac{p_z^F(\tau)}{p_y^F(\tau)} = \frac{p_z(z(\tau), y^*(\tau))}{p_y(z(\tau), y^*(\tau))} = \frac{\beta}{1-\beta} . \frac{A_y^{F*}(\tau)}{A_z^F(\tau)} . \frac{\bar{L}^*}{\bar{L}}, \tag{6.30}$$

where $\frac{p_z(z(\tau),y^*(\tau))}{p_y(z(\tau),y^*(\tau))}$ denotes the relative price of the low-tech good when home specialises in the low-tech sector z and foreign in the high-tech sector y. In the free trade equilibrium, home will experience learning by doing in the low-tech sector and foreign in the high-tech sector. With unbounded learning by doing, $A_y^{F*}(\tau) = e^{g_y^*(\tau-\tau_1)}.A_y^*(\tau_1)$ and $A_z^F(\tau) = e^{g_z(\tau-\tau_1)}.A_z(\tau_1)$ for all $\tau \geq \tau_1$.

In contrast, if specialisation in foreign is *incomplete*, then the relative price of the low-tech

---

[20] With complete specialisation in the two economies, it follows that home's *actual* dynamic comparative advantage in the free trade equilibrium lies in the low-tech sector and foreign's in the high-tech sector. The initial pattern of *static* comparative advantage is reinforced over time, and specialisation will remain complete for all $\tau \geq \tau_1$.

good will be tied down by foreign's opportunity cost of low-tech production,

$$\frac{p_z^F(\tau)}{p_y^F(\tau)} = \frac{A_y^{F*}(\tau)}{A_z^{F*}(\tau)}, \tag{6.31}$$

Specialisation in foreign is assumed to remain incomplete for all $\tau \geq \tau_1$. Home will experience learning by doing in the low-tech sector, while foreign enjoys the benefits of learning by doing in both the low-tech and high-tech sectors. With unbounded learning by doing, $A_y^{F*}(\tau) = e^{g_y^*(\tau-\tau_1)}.A_y^*(\tau_1)$ and $A_z^{F*}(\tau) = e^{g_z^*(\tau-\tau_1)}.A_z(\tau_1)$ for all $\tau \geq \tau_1$.

6.10.3 Welfare Reducing Trade

Complete Specialisation

Under *complete specialisation*, the relative price of the low-tech good $p_z^F(\tau)/p_y^F(\tau)$ is determined by (6.30). Substituting for $p_z^F(\tau)/p_y^F(\tau)$ in (6.29) and evaluating the integral, we obtain the following expression for free trade intertemporal welfare,

$$U_{\tau_1}^F = \frac{\beta.[A_z(\tau_1)]^{\beta}.\left[A_y^*(\tau_1)\right]^{1-\beta}.(\bar{L}^*/\bar{L})^{1-\beta}}{\rho - \beta g_z - (1-\beta)g_y^*}, \tag{6.32}$$

Free trade will be welfare reducing relative to autarky if and only if $U_{\tau_1}^N > U_{\tau_1}^F$. From equations (6.27) and (6.32),

$$\Leftrightarrow \quad \frac{\left(\frac{1-\beta}{\beta}\right)^{1-\beta}.[A_y(\tau_1)]^{1-\beta}.\bar{L}^{1-\beta}}{\rho - \beta g_z - (1-\beta)g_y} > \frac{\left[A_y^*(\tau_1)\right]^{1-\beta}.[\bar{L}^*]^{1-\beta}}{\rho - \beta g_z - (1-\beta)g_y^*}, \tag{6.33}$$

Proposition 1 *With complete specialisation in both economies, a* necessary *condition for free trade to reduce intertemporal welfare relative to autarky is that home has an intertemporal advantage in the sector in which it initially enjoys a static comparative* dis*advantage.*

Proof. By assumption, at time τ_1, home has a static comparative advantage in low-tech production. Hence, we require $A_z(\tau_1).p_z(\tau_1)/p_y(\tau_1) > A_y(\tau_1)$. Substituting for $p_z(\tau_1)/p_y(\tau_1)$ from (6.30) and rearranging, we require $\left(\frac{1-\beta}{\beta}\right) \cdot [A_y(\tau_1)] .\bar{L} < \left[A_y^*(\tau_1)\right] .\bar{L}^*$. Thus, in order for (6.33) to be satisfied, we require $g_y > g_y^*$, that is we require home to have an intertemporal advantage in the high-tech sector.

□

The existence of *static gains* from trade means that instantaneous welfare at time τ_1 must be lower under autarky than under free trade. However, there may be either *dynamic gains* or *dynamic losses* from free trade. From equation (6.26), the rate of growth of instantaneous utility under autarky depends upon home's rates of learning in the low-tech and high-tech sectors, g_z and g_y respectively. In contrast, equation (6.29) implies that the rate of growth of instantaneous utility under free trade depends upon home's rate of learning by doing in the low-tech sector g_z and foreign's rate of learning by doing in the high-tech sector g_y^*. A necessary condition for there to be *dynamic losses* from trade is that $g_y > g_y^*$, or that home has an intertemporal advantage in the high-tech sector (the sector in which it initially has a static comparative *dis*advantage).

Even if *dynamic losses* exist, this does not necessarily mean that free trade will reduce intertemporal welfare. The sufficient condition for free trade to be welfare reducing under complete specialisation is given by the inequality in equation (6.33). In order for free trade to reduce intertemporal welfare, we require that the *dynamic losses* from trade exceed the *static gains*. That is, we require home's intertemporal advantage in the sector in which it has a static comparative *dis*advantage to be sufficiently large.

Incomplete Specialisation

In contrast, if specialisation in foreign is *incomplete*, the relative price of the low-tech good $p_z^F(\tau)/p_y^F(\tau)$ is given by (6.31). Substituting for $p_z^F(\tau)/p_y^F(\tau)$ in (6.29) and evaluating the integral, we obtain the following expression for free trade intertemporal welfare,

$$U_{\tau_1}^F = \frac{\beta^\beta(1-\beta)^{1-\beta}.A_z(\tau_1).\left[A_y^*(\tau_1)/A_z^*(\tau_1)\right]^{1-\beta}}{\rho - g_z - (1-\beta)g_y^* + (1-\beta)g_z^*}, \tag{6.34}$$

Free trade will be welfare reducing relative to autarky if and only if $U_{\tau_1}^N > U_{\tau_1}^F$. From equations (6.27) and (6.34),

$$\Leftrightarrow \quad \frac{[A_y(\tau_1)/A_z(\tau_1)]^{1-\beta}}{\rho - \beta g_z - (1-\beta)g_y} > \frac{\left[A_y^*(\tau_1)/A_z^*(\tau_1)\right]^{1-\beta}}{\rho - g_z - (1-\beta)g_y^* + (1-\beta)g_z^*}, \tag{6.35}$$

Proposition 2 *Suppose specialisation in foreign is incomplete for all $\tau \geq \tau_1$. A necessary condition for free trade to reduce intertemporal welfare relative to autarky is that home has a potential dynamic comparative advantage in the sector in which it initially has a static compar-*

ative disadvantage

Proof. By assumption, at time τ_1, home has a static comparative advantage in low-tech production: $A_y(\tau_1)/A_z(\tau_1) < A_y^*(\tau_1)/A_z^*(\tau_1)$. Thus, a necessary condition for (6.35) to be satisfied is that the denominator of $U_{\tau_1}^N$ be less than the denominator of $U_{\tau_1}^F$. That is, $g_z - g_y < g_z^* - g_y^*$. Hence, a necessary condition for (6.35) to be satisfied is that home has a dynamic comparative advantage in the high-tech sector.

□

The existence of *static gains* from trade again means that instantaneous welfare at time τ_1 must be lower under autarky than under free trade. *Dynamic gains* or *dynamic losses* from free trade may occur. As before, the rate of growth of instantaneous utility under autarky depends upon home's rates of learning in the low-tech and high-tech sectors, g_z and g_y respectively. From equations (6.29) and (6.31), the rate of growth of instantaneous utility under free trade depends upon home's rate of learning by doing in the low-tech sector g_z and foreign's rates of learning by doing in *both* the low-tech and high-tech sectors g_z^* and g_y^*.

A necessary condition for the rate of growth of instantaneous welfare under autarky to exceed the rate of growth under free trade (a necessary condition for *dynamic losses* to occur) is that home has a potential dynamic comparative advantage in the sector in which it initially has a static comparative *dis*advantage (the high-tech sector). Even if *dynamic losses* occur, this does not necessarily mean that free trade will reduce intertemporal welfare. The sufficient condition for free trade to be welfare reducing under incomplete specialisation is given by the inequality in equation (6.35). In order for free trade to be welfare reducing, we require that the *dynamic losses* from trade exceed the *static gains.* That is, we require home's potential dynamic comparative advantage in the sector in which it has a static comparative *dis*advantage to be sufficiently large.

Throughout the analysis so far, we have assumed that specialisation in home is complete. It is also possible that the free trade equilibrium will be characterised by incomplete specialisation in home. In this case, home production is incompletely specialised under both autarky and free trade. Nonetheless, levels of output in the low-tech and high-tech sectors will vary between the two regimes. In the present case, the rate of technological progress in each sector is independent of the size of output.[21] Hence, the rate of growth of instantaneous utility will be the same under both autarky and free trade, and there will be neither *dynamic gains* nor *dynamic losses* from trade. The existence of static gains from trade implies that free trade *must* raise intertemporal welfare.

In general, the rate of technological progress in a sector may depend upon the size of output. In this case, the rate of growth of instantaneous utility under incomplete specialisation in home will vary between the two regimes of autarky and free trade. *Dynamic gains* or *dynamic losses* from trade may occur, depending upon whether or not free trade increases production in sectors in which an economy has a potential dynamic comparative advantage.

---

[21] The rate of technological progress simply depends upon whether or not output is positive.

6.11 Policy Implications

The previous Section has shown that, despite the existence of static gains, the dynamic losses from trade may be sufficient to reduce intertemporal welfare relative to autarky. Furthermore, it has been possible to derive necessary and sufficient conditions for this to occur. A *necessary* condition for free trade to be welfare reducing is that an economy has an intertemporal advantage [dynamic comparative advantage] in the sector it which it has a static comparative *dis*advantage when specialisation is complete [incomplete]. The *sufficient* condition requires that this intertemporal advantage [dynamic comparative advantage] is sufficiently large.

If free trade may reduce intertemporal welfare, this immediately raises the question whether it may be welfare improving for a policy-maker to induce specialisation in sectors in which an economy does *not* currently have a *static* comparative advantage, but in which it exhibits an *intertemporal* advantage or a potential *dynamic* comparative advantage. Throughout this Section, we restrict consideration to equilibria characterised by *complete* specialisation in both economies. At time τ_1, home is assumed to have a static comparative advantage in the low-tech sector. That is,

$$\frac{A_y^*(\tau_1)}{A_z^*(\tau_1)} > \frac{p_z^F(\tau_1)}{p_y^F(\tau_1)} > \frac{A_y(\tau_1)}{A_z(\tau_1)}, \tag{6.36}$$

Under free trade, home specialises in the low-tech sector and foreign in the high-tech sector, and the free trade relative price of the low-tech good at time τ_1 is determined according to equation (6.30).[22] Now, consider a policy of *subsidising* production in the *high*-tech sector. For each unit of income earnt in the high-tech sector, individuals are assumed to receive a production subsidy of monetary value $s > 0$. The subsidy is self-financing and is assumed to be funded by a tax ξ, $0 < \xi < 1$, on wage income. Thus, the after-tax/subsidy income in the low-tech and high-tech sectors is respectively,[23]

$$w_z^S(\tau) = (1-\xi).p_z^S(\tau).A_z^S(\tau), \qquad w_y^S(\tau) = (1+s).(1-\xi).p_y^S(\tau).A_y^S(\tau), \tag{6.39}$$

For sufficiently large s, $w_y^S(\tau) > w_z^S(\tau)$ and home will no longer specialise in the low-tech sector. Hence, for a large enough subsidy, the initial pattern of *static* comparative advantage will be reversed. With complete specialisation, home specialises in the *high*-tech sector and foreign in the low-tech. The relative price of the low-tech good at time τ_1 under the subsidy is thus,

$$\frac{p_z^S(\tau_1)}{p_y^S(\tau_1)} = \frac{\beta}{1-\beta}.\frac{A_y(\tau_1)}{A_z^*(\tau_1)}.\frac{\bar{L}}{\bar{L}^*}, \tag{6.40}$$

where complete specialisation requires,[24]

---

[22] Equation (6.30) and inequality (6.36) jointly imply that at time τ_1,

$$A_z(\tau_1) > \beta/(1-\beta).\bar{L}^*/\bar{L}.A_z^*(\tau_1), \tag{6.37}$$

$$A_y^*(\tau_1) > (1-\beta)/\beta.\bar{L}/\bar{L}^*.A_y(\tau_1), \tag{6.38}$$

[23] Where the superscript S indexes the value of a variable under the subsidy.

[24] Equation (6.40) and inequality (6.43) jointly imply that at time τ_1,

$$\frac{(1+s).A_y(\tau_1)}{A_z(\tau_1)} > \frac{p_z^S(\tau_1)}{p_y^S(\tau_1)} > \frac{A_y^*(\tau_1)}{A_z^*(\tau_1)}, \tag{6.43}$$

Equilibrium under both free trade and the subsidy to the high-tech sector is illustrated in Figure 7. For the production subsidy to be self-financing, we require, $s.p_y^S(\tau).A_y(\tau) = \xi.(1+s).p_y^S(\tau).A_y(\tau)$. Hence,

$$\hat{\xi} = \frac{s}{1+s}, \tag{6.44}$$

Since specialisation is complete, home income will be determined by after-tax/subsidy income in the high-tech sector. Substituting for the equilibrium tax rate, $\hat{\xi}$, in equation (6.39), we may obtain an expression for disposable income in the high-tech sector. Instantaneous utility of the representative agent is Cobb-Douglas. Hence, in equilibrium, disposable income will be allocated to expenditure on low-tech and high-tech goods in the constant proportions β and $(1-\beta)$ respectively. Substituting for equilibrium consumption of low-tech and high-tech goods in (6.1), we obtain the following expression for the representative agent's intertemporal utility under the subsidy,

---

$$A_z(\tau_1) < (1+s).(1-\beta)/\beta.\bar{L}^*/\bar{L}.A_z^*(\tau_1), \tag{6.41}$$

$$A_y^*(\tau_1) < \beta/(1-\beta).\bar{L}/\bar{L}^*.A_y(\tau_1) \tag{6.42}$$

For values of $\beta > 1/2$, both (6.42) and equation (6.38) in a previous footnote may be satisfied. Furthermore, for sufficiently large values of s, (6.41) is compatible with equation (6.37) in a previous footnote, and with both (6.42) and (6.38). Hence, the assumption of complete specialisation under both free trade and the subsidy is validated.

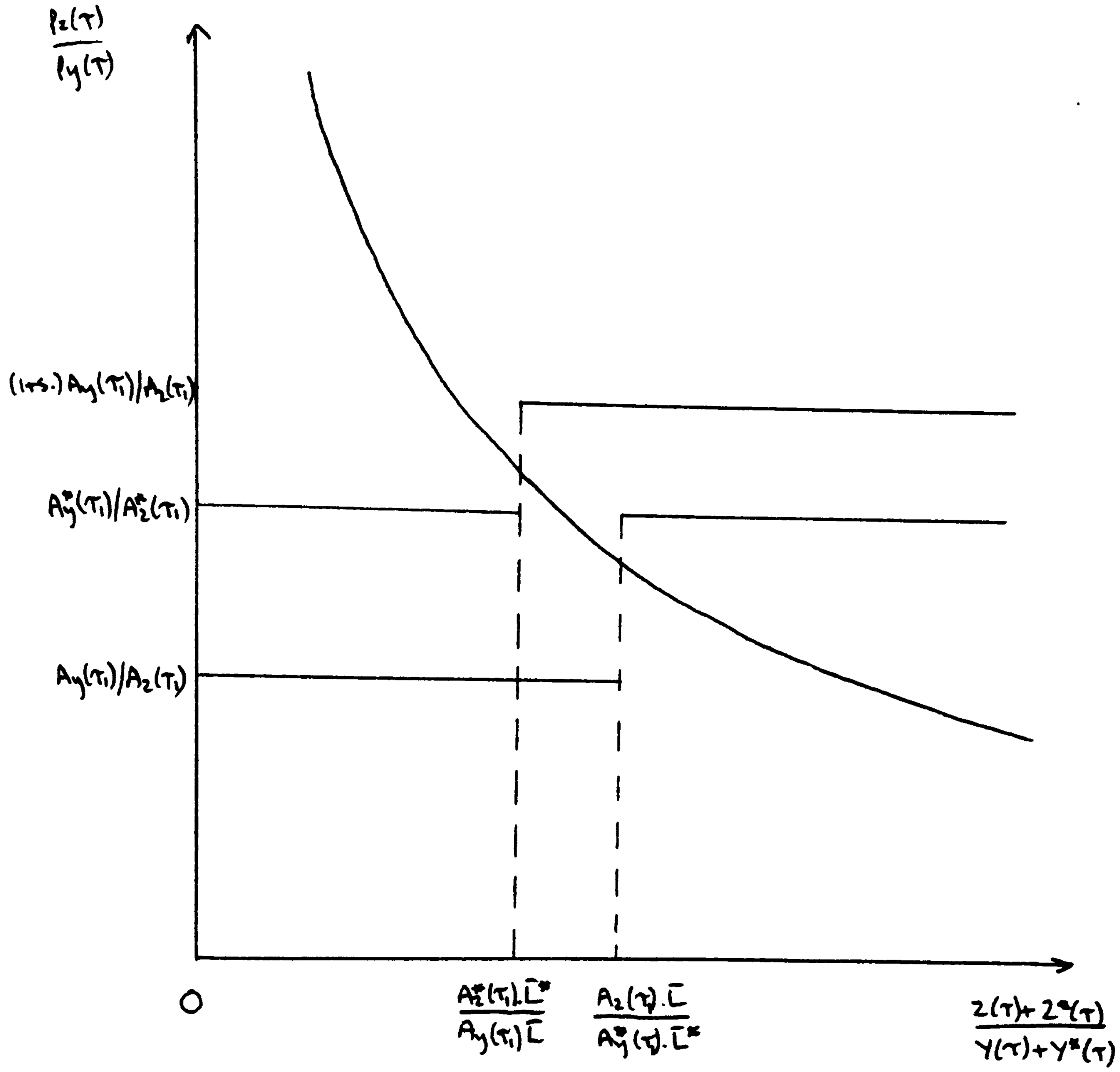


Figure 7: A subsidy-induced reversal of the initial pattern of international specialisation at time τ_1.

$$U^S_{\tau_1} = \int_{\tau_1}^{\infty} e^{-\rho(\tau-\tau_1)}.\left[\frac{\beta.p^S_y(\tau).A_y(\tau)}{p^S_z(\tau)}\right]^{\beta}.[(1-\beta).A_y(\tau)]^{1-\beta}\,d\tau, \qquad (6.45)$$

where the relative price of the high-tech good $p^S_y(\tau)/p^S_z(\tau)$ may be derived from equation (6.40). With complete specialisation, home will experience learning by doing in the high-tech sector and foreign in the low-tech. Since learning by doing is unbounded, it follows that home productivity in the high-tech sector and foreign productivity in the low-tech sector may be expressed as: $A_y(\tau) = e^{g_y(\tau-\tau_1)}.A_y(\tau_1)$ and $A^*_z(\tau) = e^{g^*_z(\tau-\tau_1)}.A^*_z(\tau_1)$ for all $\tau \geq \tau_1$. Hence, substituting for $p^S_y(\tau)/p^S_z(\tau)$ in (6.45) and evaluating the integral, we obtain the following expression for intertemporal welfare under the subsidy,

$$U^S_{\tau_1} = \frac{(1-\beta).[A^*_z(\tau_1)]^{\beta}.[A_y(\tau_1)]^{1-\beta}.(\bar{L}^*/\bar{L})^{\beta}}{\rho-\beta g^*_z-(1-\beta)g_y}, \qquad (6.46)$$

A subsidy to the high-tech sector will be welfare increasing relative to free trade if and only if $U^S_{\tau_1} > U^F_{\tau_1}$. From (6.46) and the corresponding expression for intertemporal utility under free trade with complete specialisation (6.32),

$$\Leftrightarrow \quad \frac{(1-\beta).[A^*_z(\tau_1)]^{\beta}.[A_y(\tau_1)]^{1-\beta}.(\bar{L}^*/\bar{L})^{2\beta-1}}{\rho-\beta g^*_z-(1-\beta)g_y} > \frac{\beta.[A_z(\tau_1)]^{\beta}.\left[A^*_y(\tau_1)\right]^{1-\beta}}{\rho-\beta g_z-(1-\beta)g^*_y}, \qquad (6.47)$$

Proposition 3 *A* necessary *condition for a subsidy to the high-tech sector to raise intertemporal welfare relative to* free trade *is,*

$$\beta.g_z - (1-\beta).g_y < \beta.g_z^* - (1-\beta).g_y^*,$$

Proof. See Appendix 2

The existence of static gains from trade implies that instantaneous utility at time τ_1 must be lower under the subsidy than under free trade. From equation (6.29), the rate of growth of instantaneous utility under free trade is a weighted average of home's rate of productivity growth in the low-tech sector g_z and foreign's rate of productivity growth in the high-tech sector g_y^*, with weights β and $(1-\beta)$ respectively. In contrast, equation (6.45) implies that the rate of growth of instantaneous utility under the subsidy is a weighted average of home's rate of productivity growth in the *high*-tech sector g_y and foreign's rate of productivity growth in the *low*-tech sector g_z^*, with weights β and $(1-\beta)$. If follows immediately that a **necessary** condition for the subsidy to increase intertemporal welfare is that the inequality in Proposition 3 be satisfied.

If home has a sufficiently large potential **dynamic** comparative advantage in the sector in which it has a static comparative *dis*advantage (the high-tech sector), then the inequality in Proposition 3 must be satisfied.[25] Although home initially has a static comparative advantage

---

[25] That is, if $g_z - g_y$ is sufficiently small relative to $g_z^* - g_y^*$. This follows since the inequality in Proposition 3 may be rewritten as,

$$g_z - g_y - \left(\frac{1-2\beta}{\beta}\right) g_y < g_z^* - g_y^* - \left(\frac{1-2\beta}{\beta}\right) g_y^*,$$

in the low-tech sector, by trading, it forgoes the opportunity to enjoy productivity growth in the high-tech sector. The **sufficient** condition for the subsidy to yield a higher level of intertemporal welfare than free trade is given by equation (6.47). Again, we require that home's potential **dynamic** comparative advantage in the sector where it initially has a static comparative *dis*advantage is sufficiently large.

If the subsidy is implemented, then home's *potential* dynamic comparative advantage in the high-tech sector will be translated into an actual dynamic comparative advantage. With complete specialisation, home will experience learning by doing in the high-tech sector and foreign in the low-tech sector. The initial pattern of *static* comparative advantage will be *reduced* and then *reversed* over time. Hence, at some future point in time $\tau > \tau_1$, the subsidy might be removed, and, in free trade equilibrium, home will specialise in the high-tech sector and foreign in the low-tech sector.

Although Proposition 3 establishes that the subsidy may be welfare increasing relative to free trade, we know from Proposition 1 that free trade may yield a lower level of intertemporal welfare than autarky. The policy of subsidising entry into the high-tech sector will be welfare increasing relative to *autarky* if and only if $U^S_{\tau_1} > U^N_{\tau_1}$. From (6.46) and the corresponding expression for intertemporal utility under autarky (6.27),

$$\Leftrightarrow \qquad \frac{(1-\beta)^{\beta}.[A^*_z(\tau_1)]^{\beta}.(\bar{L}^*/\bar{L})^{\beta}}{\rho-\beta g^*_z-(1-\beta)g_y} > \frac{\beta^{\beta}.[A_z(\tau_1)]^{\beta}}{\rho-\beta g_z-(1-\beta)g_y}, \qquad (6.48)$$

Proposition 4 *A* necessary *condition for a subsidy to the high-tech sector to raise intertemporal welfare relative to* autarky *is that the economy has an* intertemporal disadvantage *in the low-tech sector.*

Proof. See Appendix 2

Under the subsidy, home specialises in a sector in which it initially has a static comparative *dis*advantage. Hence, the subsidy must yield a lower level of instantaneous welfare at time τ_1 than a policy of remaining autarkic. From equation (6.26), the rate of growth of instantaneous welfare under autarky depends upon home's rate of learning by doing in the low-tech and high-tech sectors, g_z and g_y respectively. In contrast, equation (6.45) implies that the rate of growth of instantaneous welfare under the subsidy depends upon home's rate of learning by doing in the high-tech sector g_y and foreign's rate of learning by doing in the low-tech sector g_z^*. A necessary condition for the subsidy to be welfare increasing relative to autarky is thus that home has an intertemporal disadvantage in the sector where it has a static comparative advantage. The sufficient condition for the subsidy to be welfare increasing is given by equation (6.48) and requires that this intertemporal disadvantage be sufficiently large.

Thus, depending upon the pattern of *intertemporal advantage* and *dynamic comparative advantage*, it may be welfare improving for a policy-maker to subsidise entry into sectors where an economy currently has a static comparative *dis*advantage. A comparison between the subsidy and free trade is perhaps more realistic than a comparison with autarky. In this first case, an economy faces a *trade-off* between specialising according to current *static* comparative advantage and exploiting the potential pattern of *dynamic* comparative advantage. Under the subsidy, this potential will be translated into an actual dynamic comparative advantage, and the initial pattern of static comparative advantage will be reversed over time. Hence, the trade-off between static and potential dynamic comparative advantage is, in a sense, a trade-off between *current* and *future* patterns of *static* comparative advantage.

However, even though a theoretical case for a welfare-improving subsidy may exist, in practice it may be extremely difficult to determine whether an economy has an intertemporal advantage or a potential dynamic comparative advantage in a sector. Furthermore, the political economy literature suggests that any attempt to pursue an active trade policy may induce Directly Unproductive Profit-Seeking (DUP) activity and result in hidden welfare costs.[26] Hence, although a theoretical case for protectionist policies may exist, based upon the concepts of intertemporal advantage and dynamic comparative advantage, extreme caution should be taken in drawing any policy conclusions. Nonetheless, the Central and Eastern European Countries (C.E.E.C.s), with their high levels of general human capital, may well be economies where these ideas are of particular relevance.

---

[26] See for example Bhagwati (1982).

6.12 Relation to Existing Literature

The present model is closest to that of Krugman (1987), who considers a Ricardian model with sector-specific learning by doing. While Krugman refers to dynamic comparative advantage, the concept is not explicitly defined. Sector-specific learning by doing is found to reinforce the initial pattern of (static) comparative advantage. Although the analysis is not framed in these terms, this result may be reinterpreted in terms of the concepts of dynamic comparative advantage (DCA) and intertemporal advantage (IA) defined above. Unlike Krugman, we are able to undertake welfare analysis and to extend the Ricardian framework to the case of profit-seeking R & D (see Appendix 1). Furthermore, the possibility of incomplete specialisation means that an initial pattern of (static) comparative advantage may be reduced rather than reinforced over time.

Matsuyama (1992) considers the relationship between agricultural productivity and economic development. Interestingly, increases in agricultural productivity have a positive effect upon growth in a closed economy and a negative effect in an open economy. The explanation for the negative effect in the open economy is that higher productivity in the farm sector reduces specialisation in manufacturing where sector-specific learning by doing is assumed to occur. The analysis is restricted to the case of a small open economy, and hence is not so easily interpreted in terms of the concepts of IA and DCA. Nonetheless, the intuition is that the manufacturing sector exhibits greater potential for productivity growth than the agricultural sector.

Krugman (1981) considers the rationale for the doctrine of "*uneven development*": the idea that there is an inherent tendency for international income inequality to rise over time. The world consists of two economies, each of which may produce either agricultural products or manufactured goods. The manufacturing sector is assumed to be characterised by external economies to capital accumulation. As a result, a small "head start" in manufacturing production in one economy cumulates over time, as externalities to capital accumulation increase its comparative advantage in the high-tech sector. Although the production and accumulation technologies are completely different to those in the present model, the evolution of trade patterns and indeed relative incomes (as we will see in the next Chapter) may be reinterpreted in terms of the concepts of intertemporal advantage (IA) and dynamic comparative advantage (DCA).

Grossman and Helpman (1991a) consider the relationship between trade and growth, both in the case where growth results from increasing product variety (following Romer (1990)) and where it is the result of rising product quality (following Aghion and Howitt (1992)). The concept of dynamic comparative advantage is referred to (in Grossman and Helpman (1991a), Chapter 7), but not explicitly defined. Trade may either increase or decrease an economy's rate of growth, depending upon whether or not it has a (static) comparative advantage in the R & D sector.[27] Although the production and accumulation technologies again differ from the present case, this result may be explained in terms of the concepts of IA and DCA explicitly

---

[27] See also Grossman (1990) and Grossman and Helpman (1990).

defined above. Although, the free trade equilibrium is characterised by differing rates of growth of output growth, in Grossman and Helpman (1991a) both economies experience the *same* rate of growth of real consumption (and hence the same rates of growth of instantaneous utility). The more rapid productivity growth in one economy induces a continuing improvement in the terms of trade of the other economy.

Stokey (1991) and Young (1991) do find that dynamic welfare losses from free trade may occur. Moreover, if sufficiently large, these may outweigh the standard static gains from trade so that free trade reduces intertemporal welfare. The present analysis has the advantage of much greater simplicity, and may be applied to either the case of learning by doing or profit-seeking Research and Development (R & D). More importantly, we were able in this Chapter to derive *necessary* and *sufficient* conditions for free trade to be welfare reducing, and to relate these conditions to explicitly defined concepts of *intertemporal advantage* (IA) and *dynamic comparative advantage* (DCA). In addition, it was possible to show that, in certain circumstances, a policy of subsidising entry into sectors in which an economy currently has a *static* comparative *dis*advantage may be welfare improving.

6.13 Conclusion

The present Chapter has argued that, in models of endogenous innovation and trade, a distinction should be drawn between the traditional notion of *static* comparative advantage (SCA) and a second concept of *dynamic* comparative advantage (DCA). An economy is said to have a

SCA in a given sector is the opportunity cost of production at home is lower than that abroad. In order for the economy to have a DCA in a sector, we require that the rate of growth of the opportunity cost of production at home falls short of that abroad. While SCA determines the pattern of international specialisation at a point in time, DCA determines its evolution over time. As such, dynamic comparative advantage (DCA) is related to an economy's ability to reallocate resources over time, which we capture by means of the concept of *intertemporal* advantage (IA).

In light of these distinctions, an economy may face a *trade-off* between specialising in sectors in which it currently has a SCA, and specialising in sectors where it has a potential DCA or IA and may therefore achieve a SCA at a future point in time. Furthermore, given the existence of intertemporal spillovers in the innovative process, the private sector need not resolve this trade-off between current and future patterns of static comparative advantage optimally.

In models of endogenous growth, international trade may have both static and dynamic effects upon intertemporal welfare. Moreover, these dynamic effects may be responsible for free trade *reducing* economic welfare. The present Chapter has established that a *necessary* condition for free trade to be welfare reducing in the case of complete [incomplete] specialisation is that an economy have an intertemporal advantage [dynamic comparative advantage] in the sector in which it has a static comparative *dis*advantage. The *sufficient* condition for free trade to be welfare reducing requires that this intertemporal advantage [dynamic comparative advantage] be sufficiently large.

Where the patterns of static and dynamic (or intertemporal) advantage conflict, then protectionist measures to induce specialisation in those sectors where an economy has a static comparative *dis*advantage may be both welfare *increasing* and self-financing. In reality, deciding upon sectors in which an economy's potential intertemporal advantage or dynamic comparative advantage is sufficiently large may be extremely difficult. This difficulty is made all the greater by political economy considerations. Nonetheless, the transition economies of Central and Eastern Europe, with their combination of low real wages and high levels of general human capital, may be a case in point.

6.14 Appendix 1: Endogenous R & D

The assumption that technological change takes the form of learning by doing is not at all essential to the results of this Chapter. This Appendix presents a dynamic Ricardian model in which profit-seeking Research and Development (R & D) is a source of endogenous growth.[28] The basic model, including endowments and consumer preferences, remains exactly as before. Time is assumed to be *discrete*, and is indexed by τ.

6.14.1 Production

The final goods production technologies in both the low- and high-tech sectors remain exactly as before, except that, in each sector, skilled labour may now be used for either final goods

---

[28] For an alternative approach to introducing profit-seeking R & D into a Ricardian model, see Taylor (1991).

production or Research and Development (R & D).

Production in each sector $j = y, z$ is assumed to be characterised by free entry. The representative individual i in sector j is assumed to decide upon the fraction of each period of time τ, $\phi_j(\tau)$, to devote to Research and Development (R & D) and the corresponding fraction $(1 - \phi_j(\tau))$ to devote to final goods production. Since individuals are identical, in equilibrium, all individuals in a given sector devote the same fraction of time to R & D. Moreover, (as will be established below) the representative individual's research decision is stationary. Hence, in equilibrium ϕ_j is independent of time.

The flow of final goods output produced by a representative agent in each sector at time τ is thus,

$$z(\tau) = A_z(\tau).(1 - \phi_z), \tag{6.49}$$

$$y(\tau) = A_y(\tau).(1 - \phi_y), \tag{6.50}$$

where $A_z(\tau)$ and $A_y(\tau)$ denote the stocks of knowledge available for production in the low- and high-technology sectors respectively. Production in foreign is directly analogous, except that A_z^*, A_y^*, ϕ_z^* and ϕ_y^* may differ from their values in home.

6.14.2 Research

For simplicity, we assume that the research technology is deterministic and instantaneous. At the beginning of each period τ, the representative individual in each sector j ($j = z, y$) inherits a stock of production knowledge $A_j(\tau - 1)$ from the previous period. That representative individual then decides upon the fraction of period τ, ϕ_j, to allocate to research. An individual who undertakes research in sector j for an amount of time ϕ_j is assumed to raise the quality or productivity of final goods output by the constant proportion $(1 + \gamma_j.\phi_j)$, where $\gamma_j \geq 0$ and $j = z, y$. This research technology follows Aghion and Howitt (1992), and the quality or productivity of the final goods technology employed in sector j in period τ is thus,

$$A_j(\tau) = (1 + \gamma_j.\phi_j)\, A_j(\tau - 1), \tag{6.51}$$

The research technology in foreign is directly analogous, except that γ_z^*, γ_y^*, ϕ_z^* and ϕ_y^* need not equal their values in home. Innovations are assumed to be protected by a one-period patent, after which all research discoveries become common knowledge. Production knowledge spills over perfectly across periods. Hence, at the beginning of period τ, all individuals have access to the same stock of production knowledge.

6.14.3 General Equilibrium

The present model consists of two-sectors (low-tech and high-tech), each of which is essentially a composite of final goods production and research. Under both autarky and free trade, we may solve for equilibrium in two stages. Firstly, we solve for the equilibrium allocation of time to research in a sector for each allocation of skilled labour between the low- and high-tech sectors. Secondly, given equilibrium research effort as a function of the allocation of skilled labour, we solve for the equilibrium allocation of skilled labour between the two sectors.

Equilibrium Research Effort

As specified above, the representative agent's equilibrium allocation of time to research in each sector will be independent of the size of that sector. If equilibrium output in a sector j is strictly positive, then a constant fraction of time ϕ_j will be allocated to research and a corresponding fraction $(1-\phi_j)$ to current production. In each period τ, the representative individual in sector j $(j = z, y)$ chooses ϕ_j to maximise the period τ returns from final goods production in that sector,

$$\hat{\phi}_j = \left\{ \arg\max_{\phi_j} \pi_j = (1 + \gamma_j.\phi_j)\,.A_j(\tau-1).(1-\phi_j) \qquad \text{subject to } \phi_j \in [0,1] \right\}, \tag{6.52}$$

From the first-order condition to this problem, the equilibrium fraction of time devoted to research in each sector is simply,

$$\hat{\phi}_j = \begin{cases} \frac{1}{2}.\left[1 - \frac{1}{\gamma_j}\right] & \text{for } \frac{1}{2}.\left[1 - \frac{1}{\gamma_j}\right] \geq 0, \\ \\ 0 & \text{for } \frac{1}{2}.\left[1 - \frac{1}{\gamma_j}\right] < 0, \end{cases} \tag{6.53}$$

For the representative individual to have an incentive to engage in R & D, we require $\gamma_j > 1$. Under this assumption, $\hat{\phi}_j \in (0,1)$ for each sector $j = z, y$.

Equilibrium Sectoral Allocation of Resources

With free trade and zero transport costs, the relative price of the low-tech good must be the same in the two economies. With free entry into the low- and high-tech sectors, the instantaneous per period returns from production in each sector (the "wage") are respectively,

$$w_z(\tau) = p_z(\tau).A_z(\tau).(1 - \hat{\phi}_z), \tag{6.54}$$

$$w_y(\tau) = p_y(\tau).A_y(\tau).(1 - \hat{\phi}_y), \tag{6.55}$$

Specialisation at any one point in time is again determined by static comparative advantage. In equilibrium, at least one economy specialises completely. Home will specialise in the low-tech sector and foreign in the high-tech sector if and only if $w_z(\tau) > w_y(\tau)$ and $w_y^*(\tau) > w_z^*(\tau)$. That is,

$$\frac{A_y^*(\tau).(1 - \hat{\phi}_y^*)}{A_z^*(\tau).(1 - \hat{\phi}_z^*)} > \frac{p_z(\tau)}{p_y(\tau)} > \frac{A_y(\tau).(1 - \hat{\phi}_y)}{A_z(\tau).(1 - \hat{\phi}_z)}, \tag{6.56}$$

6.14.4 Static and Dynamic Comparative Advantage

The definition of *static* comparative advantage (SCA) remains exactly as before, and, for home to have a static comparative advantage in the *low*-tech good, we require,

$$\frac{A_y^*(\tau).(1-\hat{\phi}_y^*)}{A_z^*(\tau).(1-\hat{\phi}_z^*)} > \frac{A_y(\tau).(1-\hat{\phi}_y)}{A_z(\tau).(1-\hat{\phi}_z)} \tag{6.57}$$

The pattern of static comparative advantage (SCA) at any one point in time is again *endogenous*. However, not only is it endogenous, it is also the result of the *intentional* actions of profit-seeking agents. SCA depends partly upon *history* (in the form of the initial level of productivity $A_j(0)$, $A_j^*(0)$ in each sector $j = z, y$) and partly upon *equilibrium research effort* $\hat{\phi}_j$, $\hat{\phi}_j^*$ in each sector. Equilibrium research effort has two effects upon the pattern of SCA. On the one hand, the larger $\hat{\phi}_j$, the smaller the fraction of time devoted to current production. Hence, the lower home productivity per period in sector j. On the other hand, the larger $\hat{\phi}_j$, the greater cumulative research effort and the higher current productivity: since, from (6.51), $A_j(\tau) = \left(1+\gamma_j.\hat{\phi}_j\right)^\tau.A_j(0)$.

Similarly, the definition of *dynamic* comparative advantage (DCA) remains exactly as before. In discrete time, home will have a dynamic comparative advantage in the *high*-tech sector if and only if,

$$\frac{\frac{A_z(\tau)}{A_y(\tau)} - \frac{A_z(\tau-1)}{A_y(\tau-1)}}{\frac{A_z(\tau-1)}{A_y(\tau-1)}} < \frac{\frac{A_z(\tau)}{A_y(\tau)} - \frac{A_z(\tau-1)}{A_y(\tau-1)}}{\frac{A_z(\tau-1)}{A_y(\tau-1)}}, \tag{6.58}$$

Dynamic comparative advantage (DCA) depends upon relative rates of productivity growth in the two sectors. As before, the rate of productivity growth in each sector depends upon both the pattern of intertemporal advantage (IA) and the nature of international specialisation. The rate of technological progress in a sector is zero if output in that sector is not strictly positive.

In the present model, the rate of technological progress in each sector is determined by intentional investments in Research and Development (R & D). Hence, the pattern of intertemporal advantage (IA) (the opportunity cost of raising productivity in each sector j) depends upon the productivity of research in each sector γ_j, where $j = z, y$. Thus, home will have an intertemporal advantage (IA) in the low-tech sector if and only if $\gamma_z > \gamma_z^*$.

6.14.5 Trade Dynamics and Welfare

The analysis of the evolution of patterns of international trade over time remains exactly as before. An initial static comparative advantage (SCA) will be reduced if and only if an economy has a dynamic comparative advantage (DCA) in the sector in which it has a static comparative *dis*advantage. In equilibrium, Research and Development (R & D) only occurs in a sector if output in that sector is positive. Hence, trade dynamics depend crucially upon whether specialisation in an economy is complete or incomplete.

Again, there may be a *trade-off* between either exploiting the *current* pattern of static comparative advantage (SCA) or specialising in sectors in which one may gain such an advantage in the *future*, as a result of the *potential* pattern of dynamic comparative advantage (DCA). Depending upon the patterns of DCA and intertemporal advantage (IA), free trade may be welfare reducing and protectionism welfare increasing.

6.15 Appendix 2

6.15.1 Proof of Proposition 3

Inequalities (6.36) and (6.43) jointly imply,

$$\frac{(1+s).A_y(\tau_1)}{A_z(\tau_1)} > \frac{p_z^S(\tau_1)}{p_y^S(\tau_1)} > \frac{A_y^*(\tau_1)}{A_z^*(\tau_1)} > \frac{p_z^F(\tau_1)}{p_y^F(\tau_1)} > \frac{A_y(\tau_1)}{A_z(\tau_1)}, \tag{6.59}$$

At time τ_1, home is assumed to have a *static* comparative advantage in the low-tech sector. Hence, from (6.59), $A_z(\tau_1).\frac{p_z^F(\tau_1)}{p_y^F(\tau_1)} > A_y(\tau_1)$. Furthermore, from (6.59), $\frac{p_z^S(\tau_1)}{p_y^S(\tau_1)} > \frac{p_z^F(\tau_1)}{p_y^F(\tau_1)}$. Thus, $A_z(\tau_1).\frac{p_z^S(\tau_1)}{p_y^S(\tau_1)} > A_y(\tau_1)$. From equations (6.29) and (6.45), it follows immediately that *instantaneous* utility at time τ_1 under free trade *must* exceed instantaneous utility under the subsidy,

$$\left[\beta.A_z(\tau_1).\frac{p_z^S(\tau_1)}{p_y^S(\tau_1)}\right]^{\beta}.\left[(1-\beta).A_z(\tau_1).\frac{p_z^F(\tau_1)}{p_y^F(\tau_1)}\right]^{1-\beta} > [\beta.A_y(\tau_1)]^{\beta}.[(1-\beta).A_y(\tau_1)]^{1-\beta},$$

Hence, the numerator of the left-hand side of inequality (6.47) must be less than the numerator of the right-hand side,

$$(1-\beta).\,[A_z^*(\tau_1)]^{\beta}\,.\,[A_y(\tau_1)]^{1-\beta}\,.\,(\bar{L}^*/\bar{L})^{2\beta-1} < \beta.\,[A_z(\tau_1)]^{\beta}\,.\,\left[A_y^*(\tau_1)\right]^{1-\beta},$$

A **necessary** condition for the inequality (6.47) to be satisfied is thus that the denominator of the left-hand side be strictly less than the denominator of the right hand side. That is,

$$\beta.g_z - (1-\beta).g_y < \beta.g_z^* - (1-\beta).g_y^*,$$

□

6.15.2 Proof of Proposition 4

Since home has a *static* comparative advantage in the low-tech sector, if follows (from (6.59) in the Proof of Proposition 3 above) that $A_z(\tau_1).\frac{p_z^F(\tau_1)}{p_y^F(\tau_1)} > A_y(\tau_1)$. Since (6.59) also implies $\frac{p_z^S(\tau_1)}{p_y^S(\tau_1)} > \frac{p_z^F(\tau_1)}{p_y^F(\tau_1)}$, it follows that

$$A_z(\tau_1).\frac{p_z^S(\tau_1)}{p_y^S(\tau_1)} > A_y(\tau_1), \tag{6.60}$$

Substituting for $\frac{p_z^S(\tau_1)}{p_y^S(\tau_1)}$ in (6.60) using equation (6.40), we obtain,

$$(1-\beta).A_z^*(\tau_1).\frac{\bar{L}^*}{\bar{L}} < \beta.A_z(\tau_1)$$

Hence, the numerator of the left-hand side of inequality (6.48) must be less than the numerator of the right-hand side. A **necessary** condition for the inequality (6.48) to be satisfied is that the denominator of the left-hand side be strictly less than the denominator of the right hand side. That is,

$$g_z < g_z^*,$$

Hence, a **necessary** condition for the subsidy to be welfare improving relative to autarky is that home has an intertemporal **dis**advantage in the low-tech sector. □

Chapter 7

Leapfrogging and International Competitiveness

7.1 Introduction

The previous Chapter has been concerned with the relationship between the rate of technological change and international trade. The objective of the present Chapter is twofold. The first relates to the question of the "penalty" to being a pioneer raised earlier in this thesis. Chapter 5 argued that a penalty to being a pioneer provides one explanation for relative decline and income convergence. However, the analysis was restricted to the case of a single closed economy, where we considered the comparative static implications of pioneer status for innovation, rates of growth and economic welfare. The closed economy assumption made possible a relatively rich specification of the innovative process, in which a distinction was drawn between fundamental and secondary innovation. The first objective of the present Chapter is to extend this analysis to introduce international trade between economies. This enables an analysis of relative incomes and the evolution of the cross-section distribution of income over time.

In particular, we will be concerned with establishing *necessary* and *sufficient* conditions for an economy that starts from a low level of income per capita (a backward economy) to *catch-up* with, and then *leapfrog* or *overtake*, a second economy with a higher starting level of income per capita. The question whether or not income per capita in one economy catches-up with the level in another economy is fundamentally one of income convergence. Section 2 surveys the existing literature on income convergence, and the somewhat smaller literature concerned with the question of leapfrogging or overtaking. Section 3 extends the dynamic Ricardian model of Chapter 6 to consider the evolution of the cross-section distribution of income over time. The resulting framework is similar to Brezis *et al.* (1993), which is essentially a special case of the present analysis. Section 4 considers this special case, in which there may be persistent cycles in technological leadership, and relates the analysis to the penalty to being a pioneer in Chapter 5.

The second purpose of this Chapter is to consider the idea that an economy's living standards may be affected by its "*international competitiveness.*" This idea has been extremely popular in some circles, and it is often suggested that a deterioration in international competitiveness relative for example to Japan is responsible for the slow growth in U.S. living standards since the 1970s. Following Krugman (1994a), (1994b), (1994c) and (1995a), we argue the claim that "international competitiveness" matters is fundamentally a claim that the aggregate level or rate of growth of one economy's productivity *relative* to another is important for its living standards. This clearly relates to the question of income convergence and the penalty to being a pioneer, and we consider whether income convergence implies a fall in economic welfare in an initially advanced economy. Section 5 reviews the existing literature on competitiveness, and considers the relationship between international competitiveness and living standards in the dynamic Ricardian model of Chapter 6. Finally, Section 7 concludes.

7.2 Convergence and Leapfrogging

Whether income per capita in a backward economy *catches-up* with or *leapfrogs* income per capita in an initially advanced economy are questions as to what happens to the world cross-section distribution of income. Throughout this Chapter, we identify *catch-up* with the concept of *income convergence.* The next subsection surveys the existing literature on income convergence, while the following subsection reviews the literature on overtaking or leapfrogging.

7.2.1 Concepts of Convergence

The existing literature on income convergence across economies or regions is characterised by two broad approaches. The first or traditional approach, beginning with Barro and Sala-í-Martin (1991), distinguishes two concepts of convergence: β and σ. A cross-section income distribution is said to exhibit β-convergence if an economy's rate of growth of income per capita is *negatively* correlated with its initial level of income. The same distribution shows σ-

convergence if the cross-section dispersion of per capita incomes falls over time, where dispersion is typically measured by the sample standard deviation.

Much of the debate regarding convergence has occurred within the context of the Solow-Swan (1956) model of growth. One of the implications of this model is that, the further an economy's income per capita is from its steady-state, the higher that economy's rate of growth. Hence, if the determinants of steady-state income are the same across all economies, β-convergence should be observed. If the determinants of steady-state income vary, then β-convergence will only be observed after controlling for a variety of characteristics. This has led to a distinction between *absolute* and *conditional* convergence, where conditional convergence controls for economies' characteristics.

Evidence for absolute β-convergence only exists for similar groups of regions or economies such as U.S. States (see for example Barro and Sala-í-Martin (1991, 1992)) and the O.E.C.D. (see for example Baumol (1986) and Durlauf and Johnson (1995)). Nonetheless, once one controls for a variety of characteristics such as investment rates, population growth and school enrolment, evidence for conditional β-convergence emerges among dissimilar economies such as those included in the Summers and Heston (1988) data set (see for example Mankiw, Romer and Weil (1992)). In almost all samples, the rate of convergence to steady-state is estimated to be about 2 per cent a year. Sala-í-Martin (1994) provides estimates of σ-convergence across regions of the U.S., Japan, Europe, Spain and Canada.

However, this traditional approach to convergence has been criticised in a series of important papers by Quah (1993a), (1993b), (1996a), (1996b) and (1996c). The concept of β-convergence seems problematic for a number of reasons. Firstly, Quah (1996a) provides Monte Carlo evidence that, even if the true data generating process for the cross-sectional income distribution is a series of independent random walks, finite sample bias may still generate an estimated rate of convergence of about 2 per cent. Furthermore, this result suggests that one explanation for the *prima facie* surprising result that rates of convergence are the same (approximately 2 per cent) in very different data sets would be the unit root time series properties of the data. However, as argued by Quah (1996a), this can be only part of such an explanation. The sample standard deviations for the estimate of the rate of convergence produced by these Monte Carlo studies are much higher than for example found in most cross-section regressions.

A second, and perhaps more important criticism, is that a negative correlation between initial income per capita and growth rates (β-convergence) does not necessarily imply that the cross-section dispersion of income is falling over time (σ-convergence). As argued by Quah (1993a), β-convergence may be observed in a cross-section distribution of income with unchanged (or even rising) dispersion. In this case, β-convergence simply reflects reversion towards the mean, and to suppose that it implies a falling cross-section dispersion of income (σ-convergence) is an example of Galton's Fallacy.[1]

---

[1] See Friedman (1992) and Quah (1993a). Galton examined the heights of fathers and sons, and found that the sons of tall fathers tended to be shorter than their fathers, while the fathers of tall sons tended to be shorter than their sons. Both findings may be explained in terms of mean reversion, and do not imply that the cross-section

More formally, suppose, following Sala-í-Martin (1994) and Quah (1996a), that the log of income per capita in each economy $j = 1, ..., N$ is independently and identically distributed across the cross-section, and evolves over time according to,

$$\log y_j(\tau) = b . \log y_j(\tau - 1) + \varepsilon_j(\tau), \qquad |b| < 1, \tag{7.1}$$

$$y_j(0) \text{ independent of } \varepsilon_j(\tau), \qquad \tau \geq 1,$$

where ε is independently and identically distributed across both the cross-section and time, with zero mean and finite variance ψ^2. If N is large, then the sample variance of $\log y_j(\tau)$ may be approximated by the population variance σ_τ^2, which from (7.1) is given by,

$$\sigma_\tau^2 = b^2 . \sigma_{\tau-1}^2 + \psi^2 \tag{7.2}$$

$$\Rightarrow \qquad \lim_{\tau \to \infty} \sigma_\tau^2 = \left(1 - b^2\right)^{-1} . \psi^2,$$

The assumption $|b| < 1$ in (7.1) implies that economies' growth rates exhibit β-convergence.[2] However, σ-convergence may or may not occur depending upon whether σ_0^2 is greater or less than $\left(1 - b^2\right)^{-1} . \psi^2$. Whether or not the cross-section dispersion of incomes falls over time depends

---

dispersion of male heights is falling.

[2] $\log\left(y_j(\tau)/y_j(\tau - 1)\right) = (b - 1) \log y_j(\tau - 1) + \varepsilon_j(\tau)$.

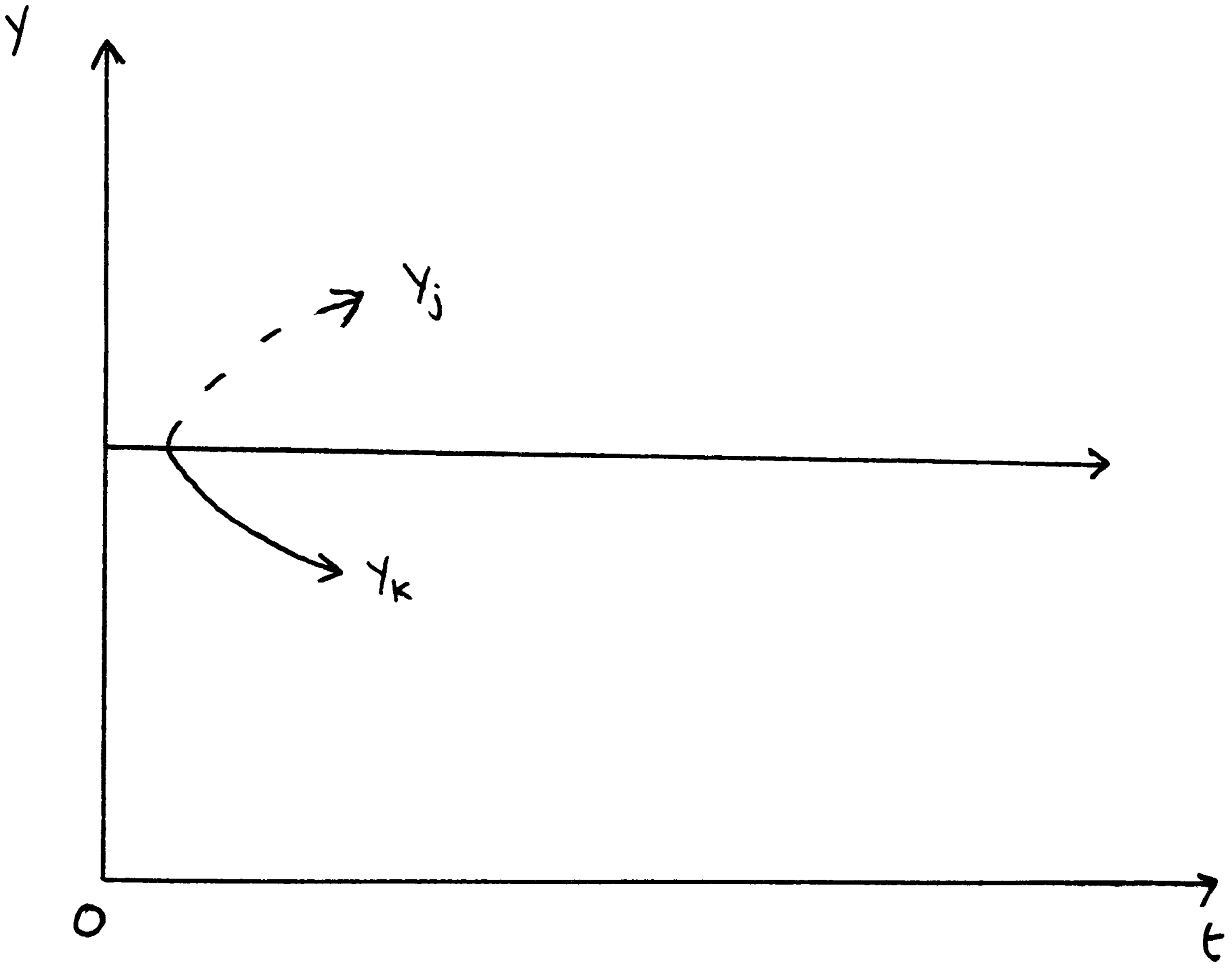


Figure 1: The Evolution of the cross-section distribution of incomes over time.

upon the initial distribution of income $Y_j(0)$. If, as in Figure 1 (a reproduction of Figure 3.1 in Quah (1996a)), we begin with an extremely even cross-section distribution of income, then σ-divergence will be observed as income evolves over time to approach a distribution where $\sigma_\tau^2 = \left(1 - b^2\right)^{-1}.\psi^2$. In this example, the concept of β-convergence is uninformative in answering the question of whether poor economies are catching up with rich.

Although β-convergence is problematic because it does not necessarily imply a falling cross-section dispersion of incomes, this does *not* mean that σ-convergence is sufficient for understanding the evolution of the cross-section distribution of income. The same level of dispersion of per capita income is consistent with widely different dynamics. Figures 2 and 3 (which reproduce Figures 3.3 and 3.4 in Quah (1996a)) show two cross-section distributions of income, where the sample standard deviation of income σ remains constant across the points in time τ_1, τ_2 and τ_3. In Figure 2, poor economies catch-up with and leapfrog rich, before themselves being caught up with and leapfrogged. In contrast, in Figure 3 the cross-section distribution of income is characterised by persistent inequality: poor economies remain poor and rich economies rich.

In the light of these problems, Quah (1993a), (1993b), (1996a), (1996b) and (1996c) has argued that an understanding of income convergence requires a complete analysis of intra-distribution income dynamics. By explicitly modelling the evolution of the entire income distribution, one is able to directly answer questions such as whether the poor catch-up with the rich, or whether the cross-section distribution of income is characterised by persistent inequality.[3]

---

[3] In an alternative approach, Durlauf and Johnson (1995) use regression tree analysis to endogenously split

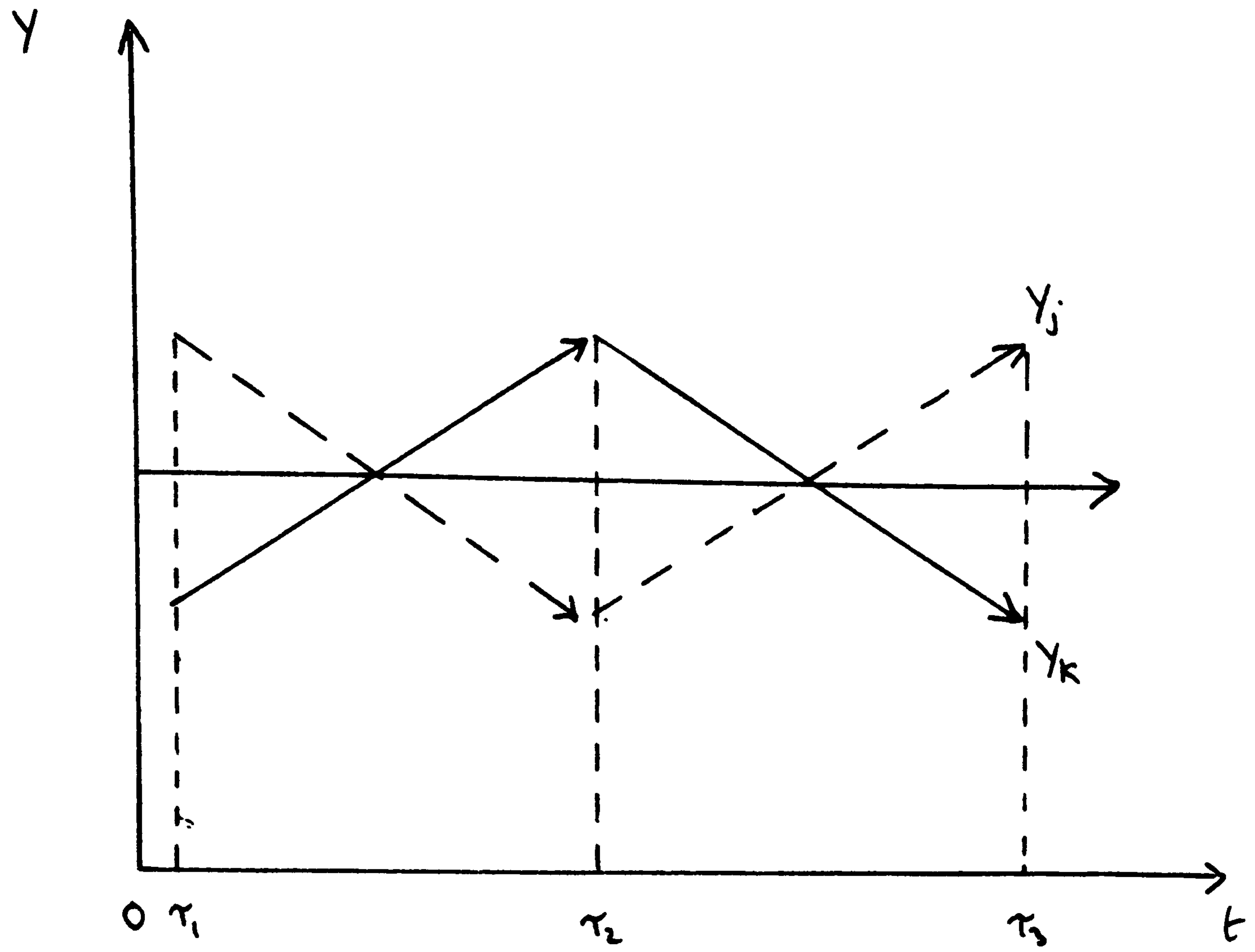


Figure 2: A constant value of σ is consistent with catch-up and leapfrogging.

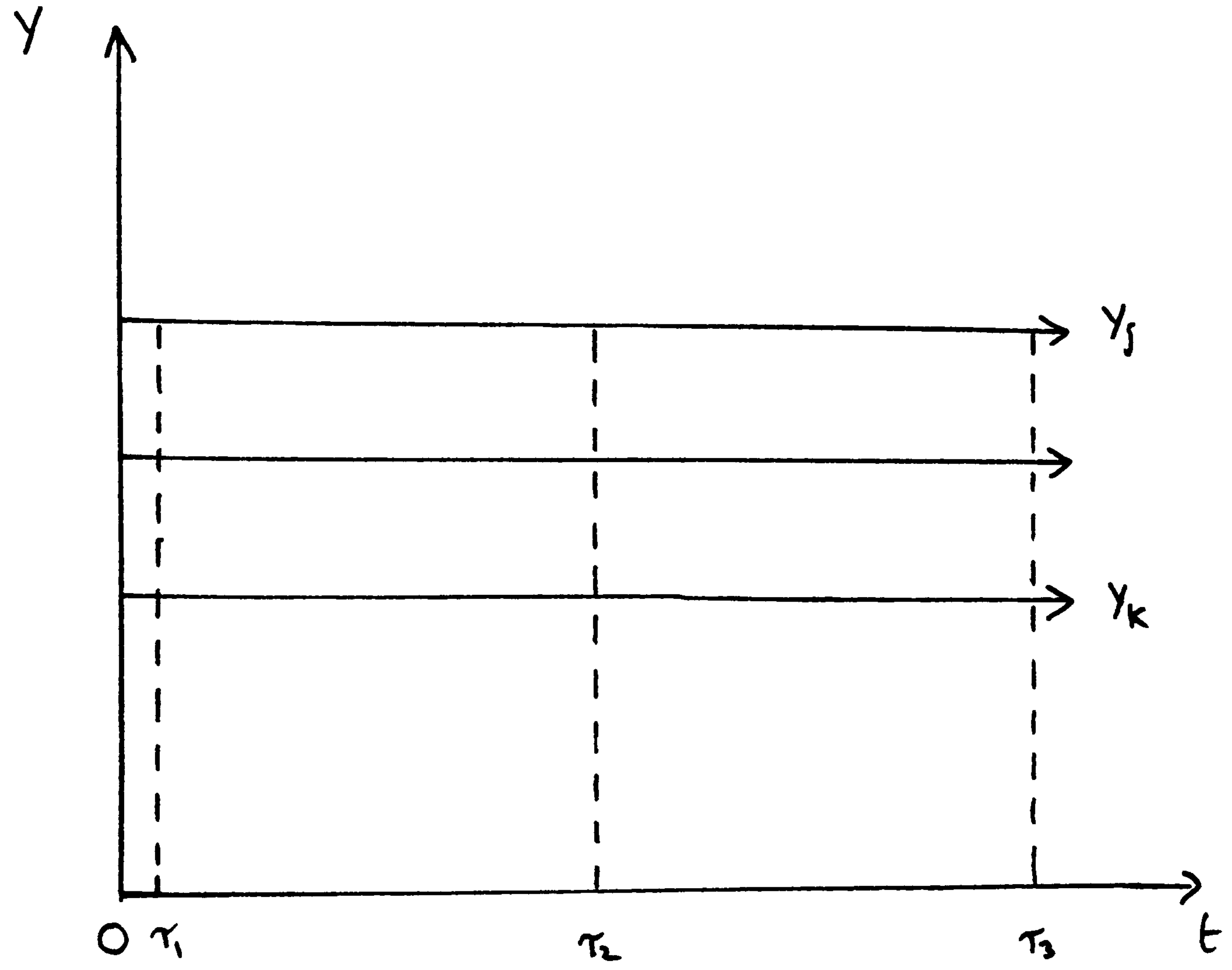


Figure 3: The same value of σ is also consistent with persistent inequality.

Quah (1993a), (1993b) and (1996a) provides empirical evidence that, in fact, the world cross-section distribution of income is characterised by considerable persistence and a polarisation of incomes into two "*convergence clubs.*"

The ergodic world distribution of income is bimodal, with "twin peaks" at high and low levels of income. Although the bimodality of the ergodic distribution might be explained within the neoclassical model,[4] the latter is inconsistent with the evidence on persistence and polarisation. The poor tend to remain poor and the rich tend to remain rich, while the middle class of incomes vanishes. Each of the "convergence clubs" constitutes a basin of attraction. Within the middle class of incomes, small variations in initial conditions may induce large differences in long-run outcomes. Hence, as in the case of the Philippines and South Korea between 1960 and 1988, two apparently similar economies may have radically different growth experiences.[5] Bliss (1995), Quah (1996b), (1996c) and García-Peñalosa (1995) are examples of theoretical models that seek to explain the empirical evidence of "convergence clubs."

In summary, the existing literature suggests that an understanding of income convergence requires a complete analysis of intra-distribution income dynamics. Throughout this Chapter, we eschew the use of the concepts of β- and σ-convergence. *Income convergence* is said to occur when income per capita in initially backward economies is *catching-up* with the levels in

---

the sample of incomes into multiple regimes. See also Temple and Johnson (1996).

[4] Suppose for example there are two sets of economies, A and B. Within each set, the determinants of steady-state income are the same. However, there are (exogenous) variations in these determinants across the two sets of economies. Conditional convergence implies that the ergodic world distribution of income will be bimodal.

[5] See for example the discussion in Lucas (1993).

more advanced counterparts. The basic framework for analysis will the two country dynamic Ricardian model of Chapter 6. Hence, the world cross-section distribution of income at each point in time is fully characterised by the incomes of the two economies, while intra-distribution dynamics depend upon the two economies' growth rates.

However, it is not only of interest whether *catch-up* (or income convergence) occurs, but also whether *leapfrogging* or *overtaking* is possible. Hence, in the next Section we turn to survey the existing literature on leapfrogging. In order to keep the analysis as simple as possible, we abstract throughout the following from the existence of convergence clubs. Thus, the analysis might be interpreted as applying within each convergence club.

7.2.2 Leapfrogging and Overtaking

In contrast to the large literature on income convergence, the idea that income per capita in one economy may *leapfrog* or *overtake* that in another has received relatively little attention. Nonetheless, leapfrogging is possible even within the Solow-Swan (1956) neoclassical model of growth. If the determinants of steady-state income vary across economies, and those economies with low initial levels of income are the economies with high steady-state incomes, then leapfrogging will occur. As conditional convergence proceeds, income per capita in backward economies will catch-up with and overtake income per capita in their more advanced counterparts.

The same process of conditional convergence and potential for leapfrogging may characterise models of invention and imitation. Barro and Sala-í-Martin (1995b) consider one such general equilibrium model of invention and imitation. An advanced and backward economy each produce a homogenous final good using skilled labour and non-tradeable intermediate inputs. In the advanced economy (country 1), new varieties of intermediate inputs are produced through *invention* by incurring a flow cost of η_1 units of output. In contrast, the backward economy (country 2) may produce new varieties of intermediate inputs through both *invention* and *imitation.* Invention is assumed to incur a flow cost of η_2 ($\eta_2 \neq \eta_1$) units of output, while the costs of imitation $\nu_2(N_2/N_1)$ are assumed to depend upon the size of the technological gap between the backward and advanced economies.[6]

Barro and Sala-í-Martin assume that, while an economy remains behind the technological frontier, the costs of invention exceed the costs of imitation. Hence, while country 2 remains behind the technological frontier, it will expand the variety of intermediate inputs through imitation. Overtaking may or may not occur depending upon whether invention is or is not intrinsically more profitable (given η_1 and η_2) in the economy that is initially backward (country 2). If so, then country 2 will first move to the technological frontier through imitation (up to the point at which $N_2/N_1 = 1$) and then become the technological leader or advanced economy. Using a similar theoretical framework, Cameron (1996b) undertakes an empirical analysis of catch-up and leapfrog between the U.S. and Japan using industry level data. In Chemicals, Paper, Primary Metals and Electrical Machinery, Japanese Total Factor Productivity (TFP) is found to have converged to and overtaken U.S. levels by the early 1980s.

---

[6] Where N_j denotes the number of varieties of intermediate inputs discovered in country j.

Thus, the analysis of Barro and Sala-í-Martin establishes that models of endogenous technological change may generate catch-up and leapfrogging. However, since each economy produces a homogenous final good, the role for international trade is somewhat limited. Motta and Thisse (1995) consider a richer, oligopolistic model of international trade, in which products are vertically differentiated (as in Shaked and Sutton (1984)). Two previously autarkic economies, starting from different levels of product quality (reflecting different conditions of domestic demand) are opened to international trade. If the initial quality gap is not too large, multiple equilibria occur. In one equilibrium leapfrogging occurs, while the second is characterised by the persistence of international leadership.

However, in each of these models, leapfrogging is a one-off phenomenon. Income per capita in one economy overtakes the level in the second economy, and a previously backward economy becomes and remains the world leader. In contrast, Brezis *et al.* (1993) argue that world may be characterised by systematic cycles of technological leadership. The example they cite is that of the Netherlands, the U.K. and the U.S.. In 1700 GDP per capita in the Netherlands exceeded the level in both the U.K. and the U.S. However, by 1820 the Netherlands had been overtaken by the U.K., and by 1950 both the Netherlands and the U.K. had been overtaken by the U.S.

The source of cycles of technological leadership in Brezis *et al.* (1993) is a contrast between normal technological progress and (exogenous) major breakthroughs, which may be interpreted in terms of the distinction between fundamental and secondary innovation introduced in Chapter 4. In Brezis *et al.* the arrival of new technologies (and hence the economy's growth rate) is *exogenous*, and there are no spillovers of secondary knowledge across technologies. There is a penalty to being a pioneer. However, the only form that it may take is technological lock-in. In Section 4, we show that Brezis *et al.* (1993) may be interpreted as a special case of the present dynamic Ricardian model, before relating their analysis to the more general model of the "penalty" to being a pioneer presented in Chapter 5.

The next Section uses the dynamic Ricardian model developed in Chapter 6 to derive *necessary* and *sufficient* conditions for both income convergence (or catch-up in per capita incomes) and overtaking or leapfrogging to occur. International trade is central to the analysis, and the potential for income convergence and leapfrogging depends crucially upon patterns of specialisation and *dynamic comparative advantage* (DCA).

7.3 A Dynamic Ricardian Model of Convergence and Leapfrogging

7.3.1 The Basic Setup

The basic model is exactly as in Chapter 6. We consider a world populated by two economies, "home" and "foreign," in which all foreign variables are denoted by an asterisk. Home and foreign may each produce two final goods: a low-technology, traditional good z and a high-technology, frontier good y. The "high-tech" good is assumed to be *high-tech* in the sense that it is characterised by both a higher level and rate of growth of productivity. The two economies are populated with continua of representative consumers of masses $\bar{L}$ and $\bar{L}^*$ respectively. Time is continuous and is indexed by $\tau \geq 0$.

Each consumer is endowed with one unit of skilled labour, which is supplied inelastically with zero disutility. We make the standard assumption that labour is perfectly mobile within economies and perfectly immobile across economies. Consumer preferences are identical in the two economies, and are assumed to be intertemporally additive separable. Instantaneous utility is Cobb-Douglas, with β and $(1-\beta)$ denoting the share of consumption expenditure allocated to low- and high-tech goods respectively.

Low- and high-technology goods are produced with skilled labour according to constant returns to scale technologies, which differ solely in terms of their productivities A_z and A_y. The productivity of final goods production in each sector is assumed to rise over time as technological progress occurs. In order to keep the analysis as simple as possible, we initially follow Chapter 6 in assuming that technological change is one-dimensional. Innovation may be the result of either bounded/unbounded learning by doing or profit-seeking Research and Development (R & D). In the case of unbounded learning by doing, productivity in each sector $j = z, y$ is assumed to depend both upon exogenous factors ψ_j (such as climate, institutions and laws) and sector-specific production knowledge $K_j(\tau)$,

$$A_z(\tau) = \psi_z.K_z(\tau) \qquad \text{and} \qquad A_y(\tau) = \psi_y.K_y(\tau), \tag{7.3}$$

where sector-specific production experience evolves over time according to,

$$\dot{K}_z(\tau) = \begin{cases} g_z.K_z(\tau) & \text{for} \quad z > 0 \\ 0 & \text{for} \quad z = 0 \end{cases}, \qquad g_z > 0, \tag{7.4}$$

$$\dot{K}_y(\tau) = \begin{cases} g_y.K_y(\tau) & \text{for} \quad y > 0 \\ 0 & \text{for} \quad y = 0 \end{cases}, \qquad g_y > 0, \tag{7.5}$$

In the case of profit-seeking Research and Development (R & D), we abstract from exogenous differences in productivity across sectors. Hence,

$$A_z(\tau) = (1 + \gamma_z.\phi_z).A_z(\tau - 1), \tag{7.6}$$

$$A_y(\tau) = (1 + \gamma_y.\phi_y).A_y(\tau - 1), \tag{7.7}$$

where ϕ_j denotes the fraction of resources devoted to research in each sector $j = z, y$. Throughout the analysis that follows, we will largely be concerned with the case of *unbounded learning by doing.* However, the analysis is easily repeated for bounded learning by doing or Research and Development (R & D), both of which will be referred to at various points.

We begin by solving for free trade equilibrium, and then consider the evolution of the two economies' incomes under complete and incomplete specialisation.

7.3.2 Free Trade Equilibrium

Suppose that trade is opened between the two previously autarkic economies, home and foreign, at some time $\tau_1 > 0$. Free trade equilibrium is defined by two sets of relationships. Firstly, since instantaneous utility in the two economies is Cobb-Douglas, world demand for the low-tech good *relative* to the high-tech good is,

$$RD_z(\tau) \equiv \frac{C_z^W(\tau)}{C_y^W(\tau)} \equiv \frac{C_z(\tau) + C_z^*(\tau)}{C_y(\tau) + C_y^*(\tau)} = \frac{\beta}{1-\beta}.\frac{p_y(\tau)}{p_z(\tau)}, \tag{7.8}$$

Secondly, perfect competition implies that the wage in the low- and high-tech sectors at home is given respectively by,[7]

$$w_z(\tau) = A_z(\tau).p_z(\tau), \qquad \text{and} \qquad w_y(\tau) = A_y(\tau).p_y(\tau), \tag{7.9}$$

where an analogous expression also holds in foreign. If specialisation in one of the two economies is incomplete, then we require that the wage in the two sectors be equal.

Throughout this Chapter, we consider free trade equilibria in which *home's initial static comparative advantage lies in the low-tech sector and foreign's in the high-tech sector.* Home is assumed to be the initially backward economy (with a low starting level of GDP per capita)

---

[7] In the case of profit-seeking Research and Development (R & D), the assumption of perfect competition is replaced by the assumption of free entry into research. The "wage" is replaced by the expected per period return to entering each sector. Hence, from Chapter 6,

$$w_z(\tau) = p_z(\tau).A_z(\tau).(1-\phi_z) \qquad \text{and} \qquad A_y(\tau) = p_y(\tau).A_y(\tau).(1-\phi_y),$$

and foreign its more advanced counterpart. Interestingly, the potential for income convergence and overtaking depends crucially upon whether specialisation is complete or incomplete.

7.3.3 Complete Specialisation

With complete specialisation,

$$\frac{A_y^*(\tau)}{A_z^*(\tau)} > \frac{p_z(\tau)}{p_y(\tau)} > \frac{A_y(\tau)}{A_z(\tau)}, \tag{7.10}$$

Home specialises in the low-tech sector and foreign in the high-tech sector. Hence, the relative supply of the low-tech good is given by $RS_z(\tau) = \frac{A_z(\tau).\bar{L}}{A_y^*(\tau).\bar{L}^*}$. In equilibrium, relative demand equals relative supply, and hence from (7.8),

$$\frac{p_z(\tau)}{p_y(\tau)} = \frac{\beta}{1-\beta}.\frac{A_y^*(\tau)}{A_z(\tau)}.\frac{\bar{L}^*}{\bar{L}}, \tag{7.11}$$

Under the assumption of perfect competition, home GDP per capita is given by the wage in the low-tech sector,

$$w(\tau) = p_z(\tau).A_z(\tau), \tag{7.12}$$

Similarly, under the assumption of perfect competition, foreign GDP per capita is given by the wage in the high-tech sector,

$$w^*(\tau) = p_y(\tau).A_y^*(\tau), \tag{7.13}$$

Thus, from (7.12), (7.13) and (7.11), home's relative income per capita Ω is simply,

$$\Omega(\tau) \equiv \frac{w(\tau)}{w^*(\tau)} = \frac{w}{w^*} = \frac{\beta}{1-\beta}.\frac{\bar{L}^*}{\bar{L}}, \tag{7.14}$$

Since home is assumed to be the initially backward economy, we assume $\Omega(\tau) = \Omega < 1$. Home relative income is increasing in the share of consumer expenditure devoted to the low-tech good β relative to that devoted to the high-tech good $(1-\beta)$, and in the size of foreign relative to home $\bar{L}^*/\bar{L}$.

Relative income depends solely upon exogenous parameters of the model, and is constant over time. There is *no potential* for income convergence or leapfrogging to occur. On the one hand, an increase in foreign productivity in the high-tech sector has a direct effect in equation (7.13) of increasing foreign income per capita. On the other hand, from equation (7.11), the increase in foreign productivity has the indirect effect of reducing the relative price of the high-tech good, thereby conveying a terms of trade gain on home. The net effect is to leave home relative income $\Omega \equiv w/w^*$ unchanged. The initial pattern of international specialisation is reinforced over time as technological progress occurs. This is illustrated in Figure 4, which reproduces Figure 3 from Chapter 6.

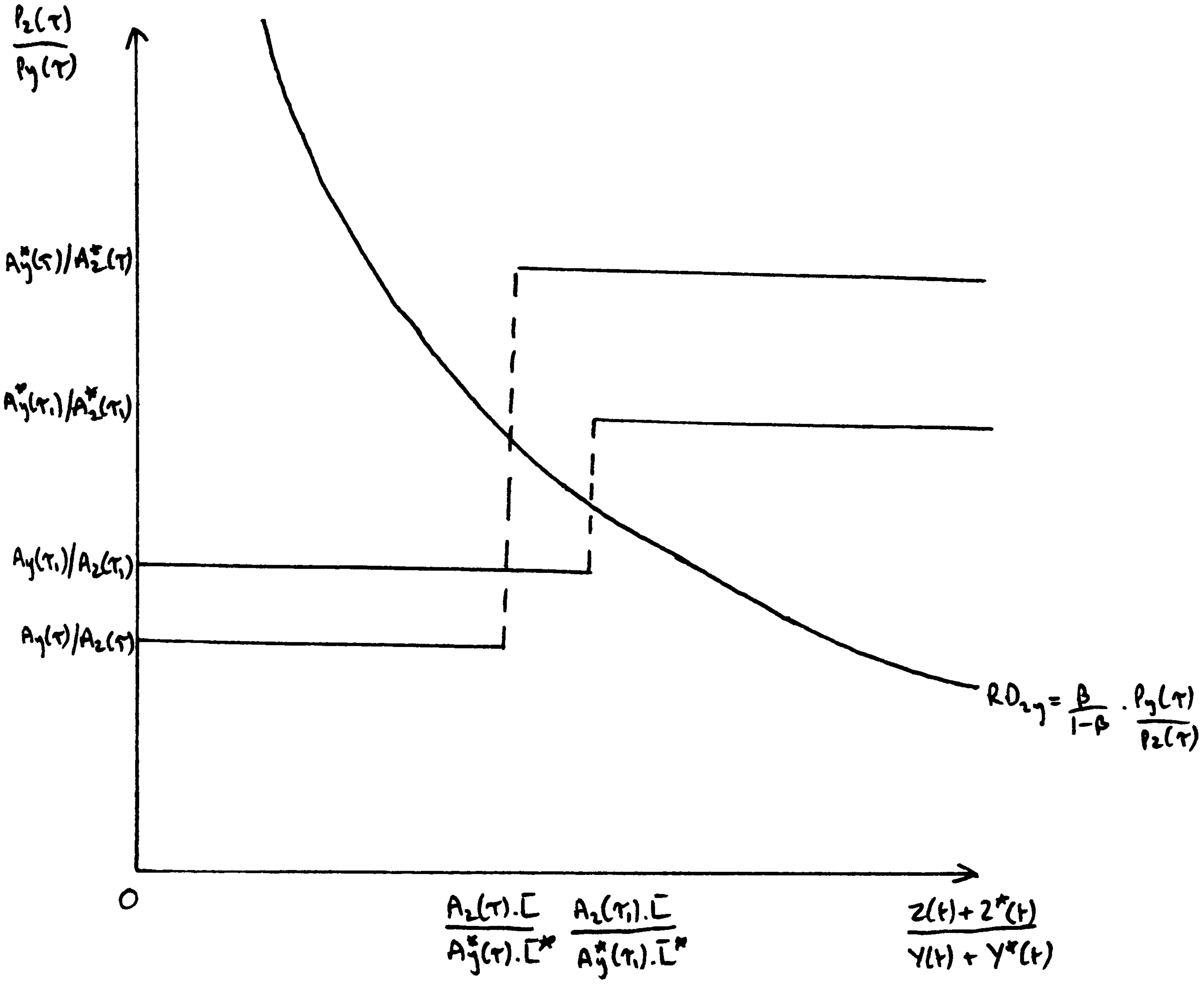


Figure 4: Free Trade Equilibrium under complete Specialisation.

7.3.4 Incomplete Specialisation

In free trade equilibrium, at least one of the economies may be incompletely specialised. Throughout this Section, we will largely be concerned with equilibria in which the backward economy (home) is initially incompletely specialised and the advanced economy (foreign) specialises in the high-tech sector. However, the analysis is directly analogous for the case where foreign is incompletely specialised and home specialises in the low-tech sector. In the case where *home* is incompletely specialised,

$$\frac{A_y^*(\tau)}{A_z^*(\tau)} > \frac{p_z(\tau)}{p_y(\tau)} = \frac{A_y(\tau)}{A_z(\tau)}, \tag{7.15}$$

The relative price of the low-tech good is tied down by the opportunity cost of low-tech production in home. Home income per capita is given by the wage $w(\tau)$, which, with incomplete specialisation, is the same in both sectors,

$$w(\tau) = p_z(\tau).A_z(\tau) = p_y(\tau).A_y(\tau), \tag{7.16}$$

As before, foreign income per capita is given by the wage in the high-tech sector,

$$w^*(\tau) = p_y(\tau).A_y^*(\tau), \tag{7.17}$$

Hence, from (7.16), (7.17) and (7.15), home relative income per capita Ω is given by,[8]

$$\Omega(\tau) \equiv \frac{w(\tau)}{w^*(\tau)} = \frac{A_y(\tau)}{A_y^*(\tau)} = \frac{\psi_y}{\psi_y^*}.\frac{K_y(\tau)}{K_y^*(\tau)}, \tag{7.18}$$

Home relative income per capita depends solely upon relative productivity in the high-tech sector, which in turn depends upon a variety of exogenous factors (parameterised by ψ_y and ψ_y^*) and the endogenous stocks of sector-specific production experience $K_y(\tau)$ and $K_y^*(\tau)$. The analysis is directly analogous for profit-seeking Research and Development (R & D). In this case, home's relative income $\Omega(\tau)$ depends upon the relative values of cumulative research effort $A_y(\tau-1)$, the equilibrium fraction of period τ devoted to research ϕ_y and the productivity of research γ_y in the high-tech sector.[9] By assumption, home is the backward economy at time τ_1, and $\Omega(\tau_1) < 1$.

Proposition 1 *Suppose that two previously autarkic economies trade from time $\tau_1 > 0$ onwards. A necessary and sufficient condition for the backward economy's income to converge towards the level of its more advanced counterpart is for specialisation in one economy to be incomplete and for the backward economy to have an intertemporal advantage in the sector where each economy is active.*

---

[8] In the case where foreign is incompletely specialised and home specialises in the low-tech sector, it is straightforward to show that $w(\tau)/w^*(\tau) = A_z(\tau)/A_z^*(\tau)$.

[9] From the above,

$$\Omega(\tau) = \frac{(1+\gamma_y.\phi_y).A_y(\tau-1).(1-\phi_y)}{(1+\gamma_y^*.\phi_y^*).A_y^*(\tau-1).(1-\phi_y^*)},$$

Proof. See Appendix.

In the example above, the backward economy (home) is incompletely specialised, while the advanced economy (foreign) specialises in the high-tech sector. Higher home productivity in the high-tech sector has both a direct effect of raising the home real wage (7.16) and an indirect effect of reducing the relative price of the high-tech good, $p_y/p_z = A_z/A_y$. Although the latter reduces home's income per capita, it also reduces foreign's income per capita as a result of the implied deterioration in foreign's terms of trade. From (7.18), incomes will converge if and only if home's rate of productivity growth in the high-tech sector exceeds foreign's. That is, we require home to have an *intertemporal* advantage (IA) in the high-tech sector.

In the case where the advanced economy (foreign) is incompletely specialised, higher home productivity in the low-tech sector imposes the terms of trade loss on foreign. In each case of *incomplete* specialisation, an increase in the backward economy's productivity in the sector where both economies are active imposes a terms of trade *loss* on the advanced economy. As a result, income convergence is possible. With *complete* specialisation, an increase in the backward economy's (home's) rate of productivity growth still has a direct effect of raising home income per capita. However, with the two economies specialising in different sectors, the indirect effect is to convey a terms of trade *gain* of equal magnitude on the advanced economy. Hence, income convergence can never occur.

In the following, we return to the case where *home* is incompletely specialised. In both the case of unbounded learning by doing and the model of profit-seeking Research and Development (R & D), it is true that, if home has an intertemporal advantage (IA) in the high-tech sector at time $\tau_1 > 0$, it will retain such an advantage for all $\tau \geq \tau_1$. As long as both economies continue to produce high-tech goods, home relative income will continue to be given by (7.18).[10] Hence, home relative income at time $\tau \geq \tau_1$ may be expressed as,

$$\frac{w(\tau)}{w^*(\tau)} = \frac{A_y(\tau)}{A_y^*(\tau)} = \frac{e^{g_y(\tau-\tau_1)}.A_y(\tau_1)}{e^{g_y^*(\tau-\tau_1)}.A_y^*(\tau_1)}, \tag{7.19}$$

where $A_y(\tau_1)/A_y^*(\tau_1) < 1$. From (7.19), it is straightforward to show that there exist finite values of time τ, at which income per capita in the backward economy will catch-up with and leapfrog the level in its more advanced counterpart.

Proposition 2 *Suppose that at time $\tau_1 > 0$, the backward economy (home) is incompletely specialised and the advanced economy (foreign) specialises in the high-tech sector. If the backward economy has an intertemporal advantage in the high-tech sector and each economy continues to produce high-tech goods, then* (i) *there exists a finite value of time $\tau_2 > \tau_1$ at which income per capita in the backward economy catches-up with the level in its more advanced counterpart,* (ii)

after

~~*there exists a finite value of time $\tau_3 > \tau_2$ at*~~ *which overtaking or leapfrogging occurs.*

Proof. See Appendix

---

[10] We have shown above that, if home is incompletely specialised and foreign specialises in the high-tech sector, relative income is given by (7.18). It is straightforward the show that the same expression is valid for the case where home specialises in the high-tech sector and foreign is incompletely specialised. In this case, home income per capita is given by $w(\tau) = p_y(\tau).A_y(\tau)$ and foreign by $w^*(\tau) = p_y(\tau).A_y^*(\tau) = p_z(\tau).A_z^*(\tau)$.

Taking logs in (7.19), it is straightforward to evaluate the length of the interval of time ϕ until catch-up occurs ($w(\tau)/w^*(\tau) = 1$),

$$\phi \equiv \tau_2 - \tau_1 = \frac{\log A_y^*(\tau_1) - \log A_y(\tau_1)}{g_y - g_y^*},$$

The interval of time until complete income convergence occurs is monotonically increasing in the size of the initial technological gap in the high-tech sector and monotonically decreasing in the magnitude of home's intertemporal advantage (IA). From (7.18), the loss of international leadership in terms of income per capita is associated with a loss of *technological* leadership in the high-tech sector.[11] As long as home retains its intertemporal advantage in the high-tech sector, its income per capita will continue to grow more rapidly than foreign's, and once overtaking has occurred income convergence will be followed by a period of income *divergence.*

7.3.5 Income Convergence and Dynamic Comparative Advantage

In Proposition 2, we assumed crucially that each economy continued to produce high-tech goods. However, as in Chapter 6, the pattern of international specialisation is endogenously determined for all $\tau \geq \tau_1$ and this need not be the case. Again we will be concerned with the case where, at time τ_1, the backward economy (home) is incompletely specialised and the advanced economy (foreign) specialises in the high-tech sector.[12]

The backward economy (home) is assumed to have an intertemporal advantage (IA) in the

---

[11] Since, from (7.18), $w/w^* > 1$ requires $A_y(\tau) > A_y^*(\tau)$.

[12] The analysis is directly analogous for the case where foreign is incompletely specialised.

high-tech sector, so that, as long as the two economies continue to produce high-tech goods, incomes will converge. Furthermore, by assumption, home has a *static* comparative advantage (SCA) in the low-tech sector at time τ_1. The analysis of Chapter 6 suggests that, as income convergence proceeds, this initial pattern of static comparative advantage may be either *reduced* or *reinforced* over time, depending whether or not home has an actual *dynamic* comparative advantage (DCA) in the high-tech sector.

From Chapter 6, the backward economy (home) will have a dynamic comparative advantage in the high-tech sector if and only if,[13]

$$g_z - g_y < -g_y^*, \tag{7.20}$$

Home's intertemporal advantage in the high-tech sector is *not* sufficient for this condition to be met. Income convergence is compatible with the backward economy enjoying an increasing static comparative advantage in the low-tech sector if the backward economy's rate of productivity growth in the low-tech sector (g_z) is sufficiently large. Nonetheless, for a given value of g_z, the inequality in equation (7.20) must be satisfied for sufficiently large values of home's intertemporal advantage in the high-tech sector.

If home does have a dynamic comparative advantage (DCA) in the high-tech sector, then, with unbounded learning by doing, there exists a point in time $\tau_R > \tau_1$ at which the initial pat-

---

[13] Since foreign is completely specialised in the high-tech sector, $\dot{A}_z^*/A_z^* = 0$.

tern of static comparative advantage (SCA) is reversed. Figure 5 (which essentially reproduces Figure 4 in Chapter 6) illustrates the reversal of static comparative advantage over time. Home specialises in the high-tech sector and *foreign* is incompletely specialised. Home will continue to enjoy a dynamic comparative advantage in the high-tech sector if and only if,[14]

$$- g_y < g_z^* - g_y^*, \tag{7.21}$$

Since, by assumption $g_y > g_y^*$, this inequality must be satisfied for non-negative g_z^*.

The initial pattern of static comparative advantage will be reversed at a point in time τ_R where $A_y(\tau_R)/A_z(\tau_R) > A_y^*(\tau_R)/A_z^*(\tau_R)$. From this inequality, the reversal of static comparative advantage may occur *before* or *after* the point in time τ_2 at which income per capita in the backward economy catches-up with the level in the advanced economy.[15] As long as each economy continues to produce high-tech goods, home's intertemporal advantage (IA) in the high-tech sector implies (from Propositions 1 and 2) that home income per capita will grow more rapidly than foreign's. If $A_y(\tau_R) < A_y^*(\tau_R)$, home's income will continue to converge towards the level in foreign, while if $A_y(\tau_R) > A_y^*(\tau_R)$ income divergence will occur.

While foreign is incompletely specialised, the relative price of the low-tech good will be given by foreign's opportunity cost of low-tech production,

---

[14] Since home is now completely specialised in the high-tech sector, $\dot{A}_z/A_z = 0$.

[15] Home income per capita catches-up with foreign's at the point in time where $A_y(\tau) = A_y^*(\tau)$, In the inequality above, $A_y(\tau_R) < A_y^*(\tau_R)$ or $A_y(\tau_R) > A_y^*(\tau_R)$, depending upon whether home's productivity in the low-tech sector falls short of or exceeds foreign's.

$$\frac{p_z(\tau)}{p_y(\tau)} = \frac{A_y^*(\tau)}{A_z^*(\tau)}, \tag{7.22}$$

However, if home's static comparative advantage (SCA) in the high-tech sector becomes sufficiently large, then, at some point in time $\tau > \tau_R$, specialisation will become complete. As illustrated in Figure 6, home specialises in the high-tech sector and foreign in the low-tech. In this case, from equation (7.8), the relative price of the low-tech good is given by,

$$\frac{p_z(\tau)}{p_y(\tau)} = \frac{\beta}{1-\beta}.\frac{A_y(\tau)}{A_z^*(\tau)}.\frac{\bar{L}}{\bar{L}^*}, \tag{7.23}$$

Hence, from (7.22) and (7.23), complete specialisation requires,

$$A_y(\tau) > \frac{1-\beta}{\beta}.\frac{\bar{L}^*}{\bar{L}}.A_y^*(\tau), \tag{7.24}$$

Once specialisation becomes complete, then, from Section 7.3.3, the process of income convergence or divergence described above will *cease*. From equation (7.24), complete specialisation may occur *before* or *after* home income per capita has caught up with foreign's. Changes in the pattern of international specialisation, as determined by *dynamic comparative advantage* (DCA), *may affect the evolution of the cross-section distribution of income over time.*

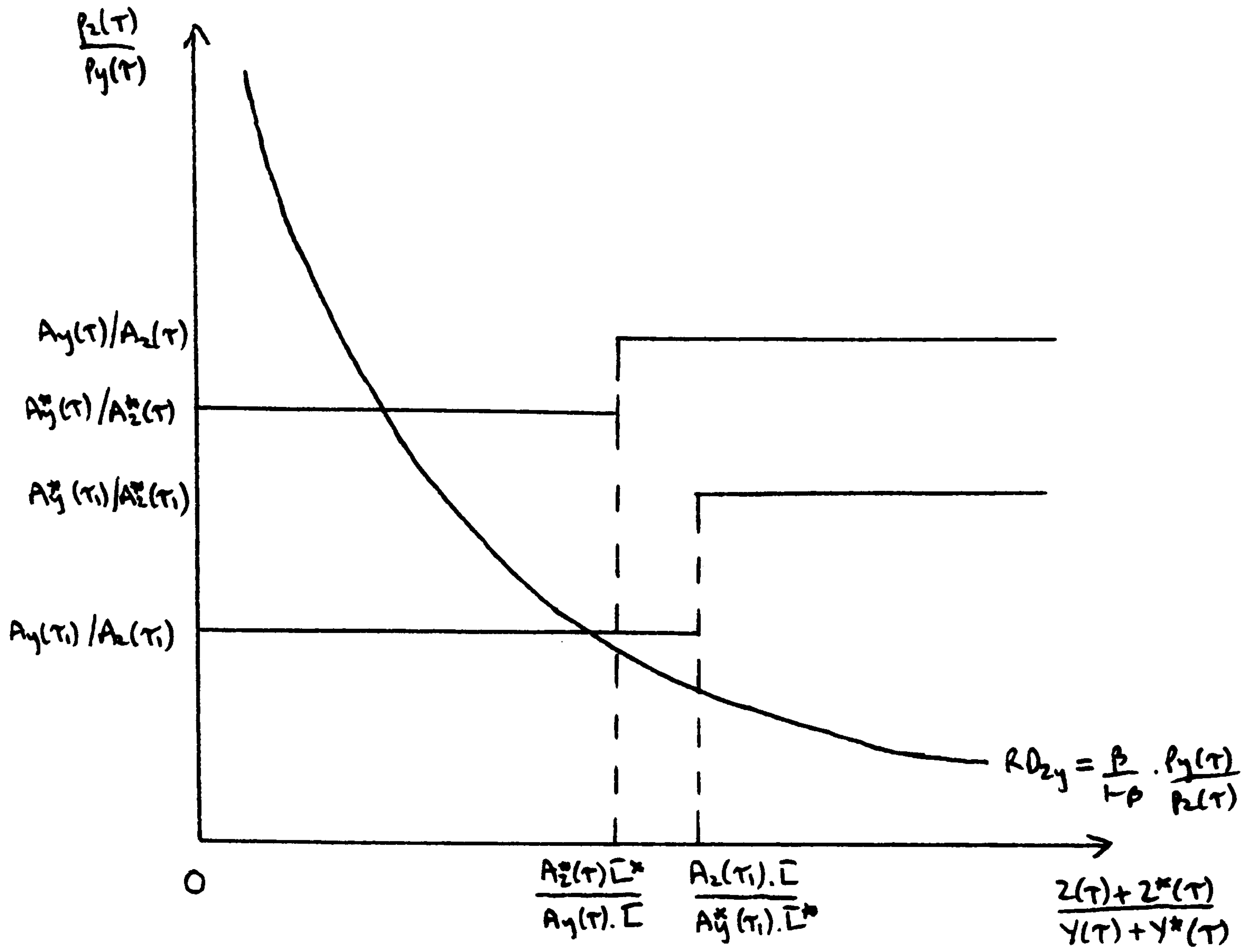


Figure 5: The reversal of static comparative advantage over time.

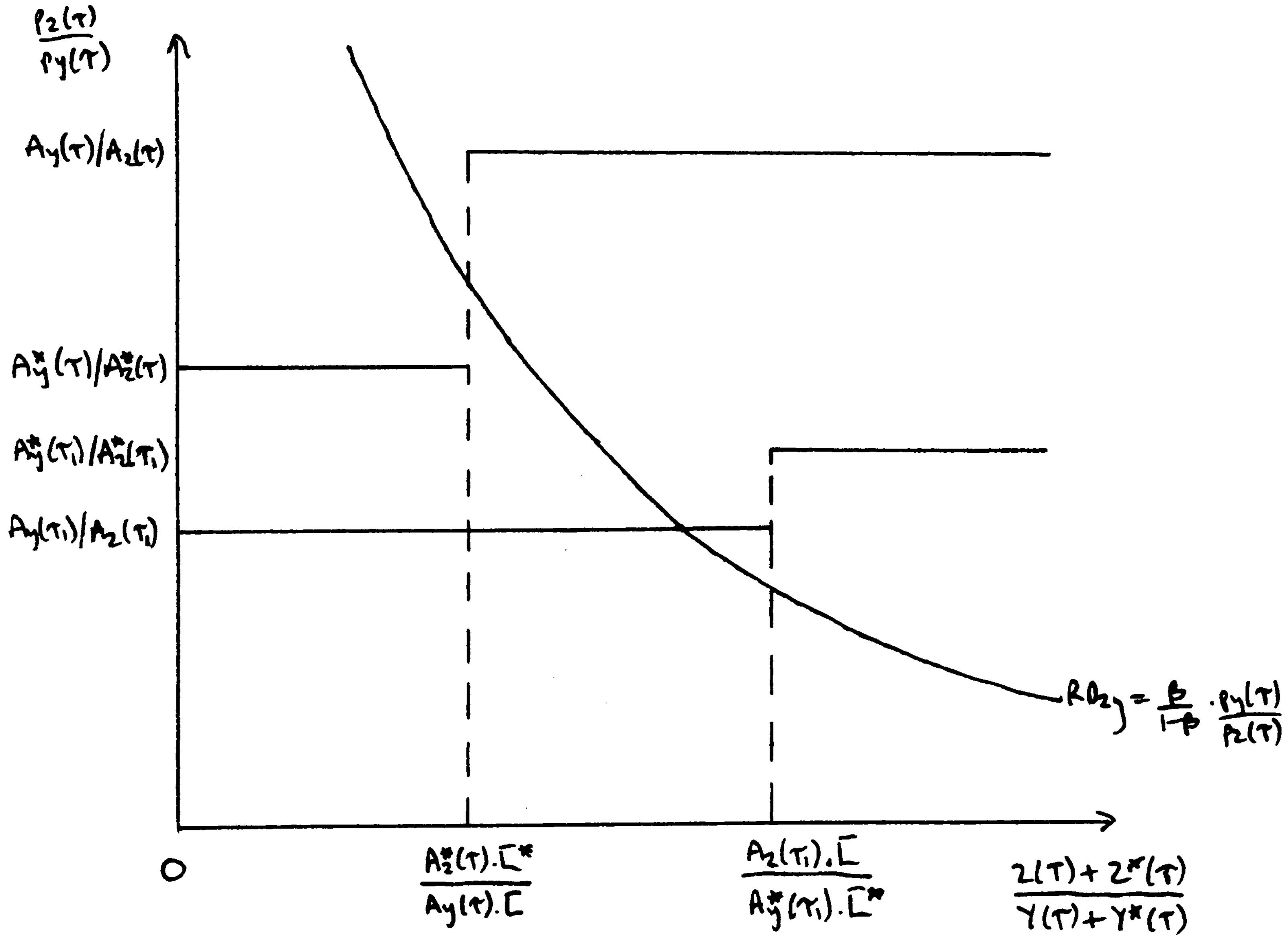


Figure 6: Specialisation may become complete at some time $\tau > \tau_1$

7.3.6 Will Incomes Converge ?

From the analysis above, *catch-up* and *overtaking* depend crucially upon specialisation being incomplete and the backward economy having an intertemporal advantage in the sector where both economies are active. However, in the case of unbounded learning by doing and profit-seeking Research and Development (R & D), intertemporal advantage (IA) is determined by technological parameters and there is no necessary reason why it should be the backward economy that has the IA.

However, *bounded* learning by doing (as specified in Chapter 6) provides a natural explanation as to why it should be the backward economy that has the IA in the high-tech sector. Hence, assuming specialisation is *incomplete*, bounded learning by doing provides a natural reason why income convergence should occur. Thus, suppose that learning by doing is bounded, as in equations (6.7) and (6.8) in Chapter 6, and that the backward economy (home) is incompletely specialised while the advanced economy (foreign) specialises in the high-tech sector.

For simplicity, we assume that the two economies share the *same* values of the exogenous determinants of productivity (ψ_j where $j = y, z$). Hence, a necessary condition for the backward economy to initially have a static comparative advantage (SCA) in the low-tech sector is,

$$\frac{K_y^*(\tau)}{K_z^*(\tau)} > \frac{K_y(\tau)}{K_z(\tau)},$$

It seems plausible that the backward economy's SCA in the low-tech sector is at least partly explained by its inexperience in the high-tech sector. Hence, we assume that it is initially true that $K_y(\tau) < K_y^*(\tau)$. If learning by doing is bounded and the two economies share the same values for the learning parameters α_y and γ_y, then this is sufficient for the backward economy to have an intertemporal advantage (IA) in the high-tech sector. The lower an economy's degree of experience in a sector, the greater the potential for learning by doing and the more rapid its rate of productivity growth.

The resulting model yields a prediction of conditional convergence similar to the Solow-Swan (1956) neoclassical model and the Barro and Sala-í-Martin (1995b) model of invention and imitation. The stock of cumulative production experience in the high-tech sector of each economy converges to the steady state values $\bar{K}_y = \alpha_y/\gamma_y$ and $\bar{K}_y^* = \alpha_y^*/\gamma_y^*$ respectively. Depending upon the relative values of $\bar{K}_y$ and $\bar{K}_y^*$ income per capita in the initially backward economy will either converge to a steady-state value below that in the initially advanced economy, or will leapfrog or overtake income per capita in the initially advanced economy.

7.4 Cycles in International Leadership

In the model of bounded learning by doing, as in Solow-Swan (1956) and Barro and Sala-í-Martin (1995b), leapfrogging, if it occurs, is once-off. In contrast, Brezis *at al.* (1993) have argued that international trade may be characterised by persistent cycles in international technological leadership. The latter consider the evolution of relative income per capita in a dynamic Ricardian model, which may be seen as essentially a special case of the model of this Chapter.

In Brezis *et al.* (1993), the low-technology and high-technology sectors are identified with food and ~~agriculture.~~ manufacturing The technology for food production is assumed to exhibit no potential for technological progress and to be the same in both economies, so that in terms of the analysis above $A_z(\tau) = A_z^*(\tau) = A_z$ for all τ. The manufacturing sector is assumed to experience two forms of technological progress: "major breakthroughs" and "normal" technological progress, which we interpret as *fundamental* and *secondary* innovations respectively. Fundamental innovations are assumed to be *exogenous*, while secondary innovation takes the form of learning by doing. Learning by doing is assumed to be entirely specific to each fundamental technology, so that there are *no* spillovers of learning by doing.

Thus, productivity in manufacturing is assumed to be a function $B_y(\cdot)$ of cumulative production experience specific to a fundamental innovation m. This function shifts out over time as (exogenous) fundamental innovations occur,

$$A_y(\tau) = B_y^m\left(K_y^m\right), \qquad \text{where} \quad B'(\cdot) > 0, \quad B''(\cdot) < 0, \tag{7.25}$$

$$\text{where} \qquad K_y^m = \int_{-\infty}^{\tau} Y^m(s)ds,$$

In Brezis *et al.* (1993), a pioneer of one major breakthrough will be characterised by a larger stock of cumulative production experience in the high-tech sector. As a result, it will enjoy higher wages and higher income per capita than an otherwise identical latestarter (which will specialise incompletely or completely in food). Suppose that, in these circumstances, an *exogenous* major breakthrough occurs. At the high real wages in the pioneering economy, it may not be profitable for any one entrepreneur to adopt the new fundamental technology, even though it is profitable for the latestarter to do so. As a result, the pioneering economy becomes *locked-into* an existing technology.

Once the latestarter has adopted the fundamental innovation, it will begin to accumulate production experience through learning by doing. If the rate of learning by doing in the latestarter is sufficiently high relative to the pioneer ($|B''(\cdot)|$ sufficiently large), then (in terms of the analysis above) the latestarter will enjoy an intertemporal advantage (IA) in the manufacturing sector and income convergence will occur until ultimately the latestarter leapfrogs the pioneer. The roles of latestarter and pioneer are reversed, and, if a second major breakthrough occurs, the whole cycle will be repeated.

While the analysis of Brezis *et al.* (1993) does provide an explanation of cycles in international technological leadership, it relies crucially upon the occurrence of exogenous major breakthroughs and the assumption of no spillovers of learning by doing. More generally, one might suppose that the rate of technological progress is the result of intentional investments by profit-seeking agents, as in the model of Research and Development (R & D) in Appendix 1 of Chapter 6. Thus, suppose that the backward economy (home) is incompletely specialised and the advanced economy (foreign) specialises in the high-tech sector. In this case, the analogue to equation (7.18) implies that, in order for home income per capita to converge towards the level in foreign, home's rate of productivity growth in the high-tech sector must exceed foreign's,

$$\frac{A_y(\tau) - A_y(\tau - 1)}{A_y(\tau - 1)} > \frac{A^*_y(\tau) - A^*_y(\tau - 1)}{A^*_y(\tau - 1)},$$

$$\Leftrightarrow \qquad \gamma_y.\phi_y > \gamma^*_y.\phi^*_y,$$

A necessary and sufficient condition for this inequality to be satisfied is that home has an *intertemporal advantage* (IA) in the high-tech sector.[16] In the model of Research and Development (R & D) in Chapter 6 this simply requires that home's research productivity in the high-tech sector exceeds foreign's, $\gamma_y > \gamma^*_y$.

Since the productivity of research γ_y is a technological parameter, the model of Chapter 6 provides no necessary reason why the backward economy should enjoy such an IA in the high-tech sector. Nonetheless, the more general, two-dimensional model of technological change proposed in Chapter 5 *does* provide a reason why a pioneer might experience a higher opportunity cost to engaging in Research and Development (R & D). From the analysis of Chapter 5, this will the case whenever fundamental innovations induce *secondary knowledge obsolescence* and *knowledge spillovers* in the research sector are sufficiently small.

In Brezis *et al.* (1993), diminishing returns to the accumulation of production experience

---

[16] That is, we require that the opportunity cost of raising productivity in the high-tech sector in home is lower than the corresponding opportunity cost in foreign.

mean that, in the absence of exogenous "major breakthroughs," growth in per income would cease. In contrast, Chapter 5 investigates the penalty to being a pioneer within a general equilibrium model of endogenous growth. Although the analysis of Chapter 5 is restricted to the closed economy, the same model of profit-seeking Research and Development (R & D) might be applied to the high-tech sector here. In this case, the penalty to being a pioneer provides an explanation for the backward economy having an *intertemporal advantage* (IA) in the high-tech sector, and hence for income convergence occurring.

In this way, the analysis of Chapter 5 may be related to an open economy setting. In contrast to Brezis *et al.* (1993), the arrival of fundamental innovations is *endogenously* determined by profit-seeking investments in Research and Development (R & D). The analysis allows for secondary knowledge spillovers in both final goods production and in the research sector. Furthermore, technological lock-in is no longer the sole source of the penalty to being a pioneer: more generally, the penalty to being a pioneer might take the form of devoting less resources to research directed at the discovery of the next fundamental innovation.[17]

The analysis provides an explanation not only for income convergence, but also for leapfrogging and overtaking. In Chapter 5, the technology for discovering fundamental innovations is stochastic. Hence, for sufficiently drastic fundamental innovations, there will be random changes in technological leadership, as researchers in one economy are successful in discovering the next

---

[17] The analysis of Chapter 5 also exhibits the feature that there need not always be a penalty to being a pioneer. If *ideas arrive before their time* and/or *secondary knowledge spillovers* in *research* are sufficiently large, there may be an advantage to an early start.

fundamental technology. In the presence of *secondary knowledge obsolescence* and sufficiently small *research spillovers*, a latestarter will devote more resources to fundamental research than a pioneer, and will hence enjoy a higher probability of research success.

In the next Section, we turn to the second of this Chapter's concerns: the relationship between "international competitiveness" and an economy's living standards or economic welfare. As part of this analysis, we consider the relationship between income convergence/relative economic decline and economic welfare in the advanced economy.

7.5 International Competitiveness

7.5.1 Introduction

The recent empirical literature on trade and growth has been concerned with at least two main questions. Firstly, since the 1970s U.S. average real wages have remained broadly constant.[18] Secondly, the 1980s saw a significant increase in wage inequality between skilled and unskilled workers in both the U.S. and the U.K.[19] In the existing literature, both of these phenomena have been related to international trade flows. Firstly, it has been alleged that the absence of real wage growth is explained by a lack of U.S. competitiveness with in particular Japan.[20] Secondly, a number of authors have argued that the rise in wage inequality is due to increased

---

[18] Over the 19 years between 1973 and 1991, real compensation of the average U.S. worker grew by only 6 per cent. Source: Krugman and Lawrence (1994).

[19] For example, between the early 1980s and the late 1980s, the ratio of the earnings of high education groups to those of low education groups in the U.S. rose by over 10 per cent (Source: Nickell and Bell (1995).) The picture remains broadly the same if one looks at the ratio of the non-production to the production wage.

[20] See for example: Tyson (1992) and Thurow (1992).

imports from low-wage, Newly Industrialised Countries (N.I.C.s).[21]

Clearly, the two phenomena may be related. In the present model, there is only one type of labour (skilled). Hence, we leave the rise in wage inequality to one side to focus upon the relationship between real wages (or more generally an economy's living standards or economic welfare) and "international competitiveness." On the one hand, a number of authors, including Thurow (1992), have argued that competition from other economies, such as Japan, is a major threat to U.S. living standards.

> " ... starting from approximately the same level of economic development, each country or region now wants exactly the same industries to insure that its citizens have the highest standards of living in the twenty-first century ... What was an era of niche competition in the last half of the twentieth century will become an era of head-to-head competition in the first half of the twenty-first century ... Head-to-head competition is win-lose. Not everyone will get those seven key industries. Some will win; some will lose."[22]

Sometimes the analysis of international competitiveness is restricted to high-technology industries.[23] Nonetheless, the conclusion generally drawn is that some form of protectionism or industrial policy is justified: "in the real world of the twenty-first century, defensive industrial policies are unavoidable."[24] and "Under these circumstances, American policy intervention to secure a more competitive supply base may be warranted, even if such intervention violates free trade or free market principles."[25]

---

[21] See for example: Leamer (1994) and Wood (1994). This position has been fiercely criticised by Lawrence and Slaughter (1993). For a more balanced view, see Krugman (1995b).

[22] Thurow (1992), pp. 30.

[23] See for example Tyson (1992).

[24] Thurow (1992), pp. 294.

[25] Tyson (1992), pp. 11.

On the other hand, this stance has been vehemently contested in a series of articles by Krugman (1994a), (1994b), (1994c) and (1995a). Part of the very problem with the competitiveness debate is defining exactly what is meant by "international competitiveness." The World Competitiveness Report defines international competitiveness as "the ability of a country to, proportionally, generate more wealth than its competitors in world markets."[26] In the present case, we follow Krugman (1994a), (1994b) in interpreting the claim that "international competitiveness" matters as the claim that either the aggregate *level* or *rate of growth* of one economy's productivity *relative* to another is important in determining its living standards.

The idea that the level or rate of growth of one economy's productivity *relative* to another is important for living standards is intuitively plausible because of the analogy with firms. In the words of the American President, an economy appears to be like a "big corporation competing in the global marketplace." However, this analogy is misleading because trade is not a zero sum game.[27] It fails to take into account the general equilibrium considerations that are central to international trade theory. Hence, Krugman argues, international competitiveness is irrelevant. The rate of growth of an economy's living standards is determined almost entirely by its domestic rate of productivity growth.

The analysis of the next Section begins by reviewing Krugman's arguments, first against the importance of relative levels of productivity, and then against the relevance of relative rates

---

[26] Worldlink (1995), pp. 38.

[27] The analogy is also misleading for a number of other reasons. For example, firms are concerned with profits, while governments should be concerned with economic welfare.

of productivity growth, in the context of the dynamic Ricardian model introduced in Chapter 6. We then proceed to make two further points. The first relates the debate concerning "international competitiveness" to the concept of *dynamic* comparative advantage (DCA): a case for protectionist policies may exist, but it is associated with DCA rather than "international competitiveness." The second point is concerned with the relationship between income convergence and welfare in advanced economies.

7.5.2 Competitiveness and economic welfare

The starting point for the analysis is the dynamic Ricardian model, introduced in Chapter 6 and developed in the previous Section. Consider the opening of trade at time $\tau_1 > 0$ between an initially backward economy (*home*) and an advanced economy (*foreign*). In light of the discussion above, home is identified with *Japan* and foreign with the *United States.* At time τ_1, we assume that Japan is incompletely specialised, while the United States specialises in the high-tech sector. Japan is assumed to have an intertemporal advantage (IA) in the high-tech sector, so that, as long as both economies produce high-tech goods, incomes will converge.

Income per capita in the United States is simply $w^{US}(\tau) = p_y(\tau).A_y^{US}(\tau)$, while relative U.S. income per capita w^{US}/w^J simply depends upon relative productivity levels in the high-tech sector. Since instantaneous utility is Cobb-Douglas, constant fractions β and $1-\beta$ of income are allocated to the consumption of low-tech and high-tech goods respectively,

$$c_z^{US}(\tau) = \beta.\frac{p_y(\tau).A_y^{US}(\tau)}{p_z(\tau)},$$

$$c_y^{US}(\tau) = (1-\beta).A_y^{US}(\tau),$$

Instantaneous utility in the U.S. at time $\tau \geq \tau_1$ is thus,

$$u\left(c_z^{US}(\tau), c_y^{US}(\tau)\right) = \left[\beta.\frac{p_y(\tau)}{p_z(\tau)}.A_y^{US}(\tau)\right]^{\beta}.\left[(1-\beta).A_y^{US}(\tau)\right]^{1-\beta}, \tag{7.26}$$

where, since Japan is incompletely specialised, $p_y(\tau)/p_z(\tau) = A_z^J(\tau)/A_y^J(\tau)$. The first point to make is that, even *if* U.S. productivity in both sectors were inferior to Japanese (the U.S. has an *absolute* disadvantage in both sectors), the standard static gains from trade would still exist. Traditional trade theory tells us that the existence of static gains from trade depends upon *comparative* rather than absolute advantage. In terms of the debate above, the aggregate or average *level* of productivity in one economy *relative* to another is *irrelevant* to the existence of static gains from trade and the case for free trade. It is not relative levels of *aggregate* productivity that matter, but relative levels of productivity in *different sectors.*

This does not establish that the relative levels of aggregate productivity have no effect on an economy's living standards. Indeed, it is certainly true from (7.26) that changes in Japanese productivity levels have an effect on U.S. economic welfare. However, the nature of this effect depends very much on the sector in which the increase in Japanese productivity occurs. This point may be made by either looking at changes in relative *levels* of productivity or relative *rates of growth*. Here, we will be concerned with relative rates of growth.

By assumption, Japan (home) is incompletely specialised and the U.S. (foreign) specialises in the high-tech sector. Since learning by doing is unbounded, Japanese and U.S. productivity in the low- and high-tech sectors may be expressed as: $A_z^J(\tau) = e^{g_z^J(\tau-\tau_1)}.A_z^J(\tau_1)$, $A_y^J(\tau) = e^{g_y^J(\tau-\tau_1)}.A_y^J(\tau_1)$, $A_y^{US}(\tau) = e^{g_y^{US}(\tau-\tau_1)}.A_y^{US}(\tau_1)$ and $A_z^{US}(\tau) = A_z^{US}(\tau_1)$ for all $\tau \geq \tau_1$. Substituting for the relative price of the high-tech good in (7.26), we obtain the following expression for instantaneous utility,

$$u^{US}(\cdot) = \left[\beta.e^{(g_z^J - g_y^J + g_y^{US})(\tau-\tau_1)}.\frac{A_z^J(\tau_1)}{A_y^J(\tau_1)}.A_y^{US}(\tau_1)\right]^{\beta} \cdot \left[(1-\beta).e^{g_y^{US}(\tau-\tau_1)}.A_y^{US}(\tau)\right]^{1-\beta}, \quad (7.27)$$

As argued by Hicks (1953) and Johnson (1955), a higher rate of productivity growth in one economy A may either increase or decrease instantaneous welfare in a second economy B, depending upon whether it is export-biased or import-biased respectively.[28] Given the pattern of international specialisation above, the U.S. exports high-tech goods and imports low-tech goods from Japan. An increase in the rate of Japanese productivity growth in the low-tech sector g_z^J reduces the relative price of low-tech goods $p_z/p_y = A_y^J/A_z^J$, thereby improving the

---

[28] The terms *export*-biased and *import*-biased are defined with reference to country A's exports and imports.

United States terms of trade and *increasing* instantaneous utility in the U.S.. Alternatively, an increase in the rate of Japanese productivity growth in the high-tech sector g_y^J has exactly the opposite effect, thereby *decreasing* instantaneous utility in the U.S.

In either case, higher Japanese productivity growth *reduces* U.S. competitiveness in one of the two senses defined above. However, the effect on U.S. living standards is completely *ambiguous*, and "international competitiveness" is completely unhelpful in determining the sign of this effect. Hence, Krugman (1994a), (1994b), (1994c) and (1995a) argues that the rate of growth of an economy's living standards is almost entirely determined by its domestic rate of productivity growth.[29] However, two further points may be made. Firstly, the analysis above noted that the existence of static gains from trade depends upon relative levels of productivity *in different sectors*, rather than on relative levels of aggregate productivity. In a similar way, Chapter 6 established that whether or not trade increases intertemporal welfare depends upon both the static gains from trade and relative rates of productivity *growth in different sectors* (rather than relative rates of aggregate productivity growth).

Thus, consider the case where higher Japanese productivity growth is import-biased (biased towards the high-tech sector). Then, higher productivity growth in Japan does indeed reduce U.S. living standards. However, this does not necessarily imply (as some of the protagonists in the competitiveness debate claim) that protectionism is justified.[30] Consider an extreme U.S.

---

[29] Krugman and Lawrence (1994) provide empirical evidence that, although the U.S. terms of trade did decline between 1970 and 1990, this decline had only a small impact on U.S. real GNP per worker.

[30] It is certainly true an import tariff may be justified on terms of trade grounds. However, this is the standard

protectionist policy of introducing a prohibitive tariff on all foreign goods, so that the U.S. moves from free trade to autarky. From Proposition 2 in Chapter 6, a necessary condition for intertemporal welfare to rise is that the U.S. has a potential dynamic comparative advantage (DCA) in the *low*-tech sector. That is,

$$g_y^{US} - g_z^{US} < g_y^J - g_z^J,$$

Higher productivity growth in the import-competing sector (the high-tech sector) in Japan will certainly make it more likely that this condition is satisfied for the U.S. However, an increase in g_y^J is far from necessary or sufficient for the condition to be satisfied. "International competitiveness" is irrelevant to the question of whether or not free trade raises intertemporal utility. This depends on relative levels and rates of growth of productivity *in different sectors* (and hence upon the concepts of SCA and DCA) rather than on their aggregate counterparts. Hence, a case for protectionism depends not on "international competitiveness," but on the pattern of *dynamic comparative advantage* (see also Proposition 3, Chapter 6). Furthermore, most protagonists in the competitiveness debate are concerned with the potential for U.S. productivity growth in the high-tech sector. Yet, in the example above, the case for protectionism rather than free trade depends upon U.S. dynamic comparative advantage (DCA) lying in the *low*-tech sector.

---

optimum tariff argument, and is unrelated to the competitiveness debate.

The second point that may be made links the discussion of income convergence in Sections 7.2 to 7.4 to living standards or economic welfare in the two economies. Concern about the "international competitiveness" of an economy is often associated with a decline in its *relative* income. Indeed, between 1973 and 1992, U.S. income per capita fell from approximately 150 per cent of the Japanese level to about 110 per cent.[31] However, a decline in the *relative* income per capita of an economy clearly does not necessarily imply a fall in its living standards or economic welfare.

Proposition 3 *Suppose* (i) *at time* τ_1*, the backward economy (home) is incompletely specialised and the advanced economy (foreign) specialises in the high-tech sector,* (ii) *the backward economy has an intertemporal advantage in the high-tech sector and each economy continues to produce high-tech goods.*

Consider an increase in the rate of productivity growth in both sectors of the backward economy (home) by the constant proportion $\vartheta > 1$*, so that* $g'_y = \vartheta . g_y$ *and* $g'_z = \vartheta . g_z$*.*

Then: (i) *the rate at which home's income per capita converges towards foreign's will rise,* (ii) *the effect upon intertemporal welfare in the advanced economy is* ambiguous.

Proof. See Appendix

Chapter 5 has already considered whether pioneer or advanced economy status in itself implies a lower level of economic welfare in an economy. Proposition 3 is concerned with the

---

[31] Source: Maddison (1995).

question whether an increase in the rate of productivity growth in a latestarter or backward economy (and hence an increase in the rate of income convergence) lowers economic welfare in the pioneer. The effect is *ambiguous*: advanced economy welfare may either rise or fall, depending whether the initial rate of productivity growth is higher in the low-tech or high-tech sectors respectively. It is this which determines whether the proportionate increase in the rate of productivity growth in the backward economy $\vartheta > 1$ is export-biased or import-biased.

7.6 Conclusion

The present Chapter has been concerned with two objectives. Firstly, we have sought to relate the closed economy analysis of the penalty to being a pioneer in Chapter 5 to the evolution of the cross-section distribution of income over time. Secondly, we have been concerned with the relevance of the concept of "international competitiveness" to an economy's standard of living.

Both issues have been addressed within the dynamic Ricardian model of Chapter 6. In a two economy setting, it was possible to derive *necessary* and *sufficient* conditions for income convergence and overtaking to occur. Income convergence and overtaking depend crucially upon the pattern of international specialisation, and its evolution over time as determined by dynamic comparative advantage (DCA). In order for incomes to converge, we require specialisation to be incomplete and the backward economy to have an intertemporal advantage (IA) in the sector where both economies are active.

In models of unbounded learning by doing and Research and Development (R & D), the pattern of intertemporal advantage is determined solely by technological parameters and there is no reason for such an intertemporal advantage to exist. Technological progress in the form of *bounded* learning by doing generates conditional convergence, and may hence explain the once-off occurrence of leapfrogging. Brezis *et al.* (1993) present a Ricardian model of systematic cycles in international leadership, which depends crucially upon the *exogenous* occurrence of major breakthroughs. More generally, one might suppose (as in the Appendix to Chapter 6) that the rate of technological progress in each sector is a function of profit-seeking investments in Research and Development (R & D). It has been argued that the closed economy model of the penalty to being a pioneer presented in Chapter 5 provides a plausible explanation as to why a backward economy might well have the intertemporal advantage (IA) necessary for income convergence to occur.

A concern about "international competitiveness" was interpreted as a concern about the *level* or *rate of growth* of aggregate productivity in one economy *relative* to another. Traditional trade theory implies that the relative *levels* of aggregate productivity are irrelevant to whether or not free trade raises instantaneous welfare. The existence of static gains from trade depends upon relative levels of productivity *in different sectors (static* comparative advantage (SCA)), and hence a lack of "international competitiveness" should not be used as an argument for protectionism. In the same way, the analysis of Chapter 6 suggests that relative rates of aggregate productivity growth are irrelevant to whether or not free trade raises intertemporal welfare.

The latter depends upon both the static gains from trade and relative rates of productivity growth across *different sectors* (*dynamic* comparative advantage (DCA)), and hence again a lack of "competitiveness" should not be used as a case for protectionism.

A concern about the lack of "international competitiveness" of an economy is often associated with a decline in its *relative* income. However, an increase in the rate of productivity growth in a backward economy, and hence an increase in the rate of income convergence, was found to have an *ambiguous* effect upon economic welfare in an advanced economy. Economic welfare may either rise or fall, depending upon whether the increase in productivity growth is export-biased or import-biased. A decline in an economy's *relative* income does not necessarily imply a fall in its standard of living.

7.7 Appendix

7.7.1 Proof of Proposition 1

International specialisation at time τ_1 may be characterised by either complete specialisation in both economies (case (A)) or incomplete specialisation in one (case (B)).

(A) The absence of income convergence when specialisation is complete follows immediately from Section 7.3.3 and, in particular, from (7.14).

(B) If specialisation is incomplete, there are two possibilities. Either (i) the backward economy (home) is incompletely specialised and the advanced economy (foreign) specialises in the high-tech sector , (ii) the advanced economy (foreign) is incompletely specialised and the backward economy (home) specialises in the low-tech sector.[32]

Proof for case (i): From (7.18), $w(\tau)/w^*(\tau) = A_y(\tau)/A_y^*(\tau)$. By assumption $w(\tau_1)/w^*(\tau_1) < 1$. A necessary and sufficient condition for income per capita in the backward economy to converge towards that of its more advanced counterpart is $\frac{\partial(w(\tau)/w^*(\tau))}{\partial\tau} > 0$,

$$\Leftrightarrow \quad \left(\frac{\dot{A}_y}{A_y}\right)_\tau - \left(\frac{\dot{A}_y^*}{A_y^*}\right)_\tau > 0,$$

That is, we require the relatively backward economy to have an intertemporal advantage in the high-tech sector. □

Proof for case (ii): In this case, $w(\tau)/w^*(\tau) = A_z(\tau)/A_z^*(\tau)$. By assumption $w(\tau_1)/w^*(\tau_1) < 1$. A necessary and sufficient condition for income per capita in the backward economy to converge towards that of its more advanced counterpart is $\frac{\partial(w(\tau)/w^*(\tau))}{\partial\tau} > 0$,

$$\Leftrightarrow \quad \left(\frac{\dot{A}_z}{A_z}\right)_\tau - \left(\frac{\dot{A}_z^*}{A_z^*}\right)_\tau > 0,$$

That is, we require the relatively backward economy has an intertemporal advantage in the low-tech sector. □

---

[32] There are two other posibilities, e.g. home is incompletely specialised and foreign specialises in the low-tech sector. However, by assumption, home has an initial static comparative advantage in the low-tech sector.

7.7.2 Proof of Proposition 2

At time τ_1 home is incompletely specialised and foreign specialises in the high-tech sector. The pattern of static comparative advantage is endogenously determined and evolves over time. Under the assumption that each economy continues to produce high-tech goods, there are two possible patterns of specialisation: (1) home continues to be incompletely specialised and foreign specialises in the high-tech sector, (2) home specialises in the high-tech sector and foreign becomes incompletely specialised.[33]

In each case, home relative income is given by relative productivity in the high-tech sector: $w(\tau)/w^*(\tau) = A_y(\tau)/A_y^*(\tau)$. Since learning by doing is unbounded, home relative income at time $\tau \geq \tau_1$ may be expressed as,

$$\frac{w(\tau)}{w^*(\tau)} = \frac{e^{g_y(\tau-\tau_1)}.A_y(\tau_1)}{e^{g_y^*(\tau-\tau_1)}.A_y^*(\tau_1)},$$

Proof of Proposition 2(i): Home income per capita will converge with foreign's at a point in time $\tau_2 > \tau_1$ at which $w(\tau_2)/w^*(\tau_2) = 1$,

$$\Leftrightarrow \quad e^{(g_y-g_y^*)(\tau_2-\tau_1)} = \underbrace{\frac{A_y^*(\tau_1)}{A_y(\tau_1)}}_{1<A_y^*(\tau_1)/A_y(\tau_1)<+\infty},$$

If home has an intertemporal advantage in the sector where both economies are active (high-

---

[33] That is, in case (2) the initial pattern of static comparative advantage is reversed over time, as will be discussed in Section 7.3.5.

tech), then $g_y > g_y^*$ and there exists a finite value for τ_2, $0 < \tau_2 < +\infty$, at which this equality is satisfied. □

Proof of Proposition 2(ii): Home income per capita will overtake foreign's at a point in time $\tau_3 > \tau_2 > \tau_1$ at which $w(\tau_3)/w^*(\tau_3) > 1$,

$$\Leftrightarrow \qquad e^{(g_y - g_y^*)(\tau_3 - \tau_1)} > \underbrace{\frac{A_y^*(\tau_1)}{A_y(\tau_1)}}_{1 < A_y^*(\tau_1)/A_y(\tau_1) < +\infty},$$

If home has an intertemporal advantage in the sector where both economies are active (high-tech), then $g_y > g_y^*$ and there exists a finite value for τ_3, $0 < \tau_3 < +\infty$, at which this inequality is satisfied. □

7.7.3 Proof of Proposition 3

Proof of (i): From equation (7.18) $w(\tau)/w^*(\tau) = A_y(\tau)/A_y^*(\tau)$, while by assumption,

$$\frac{\dot{A}_y}{A_y} - \frac{\dot{A}_y^*}{A_y^*} = g_y - g_y^* > 0,$$

$$\Rightarrow \qquad \frac{\partial w(\tau)/w^*(\tau)/\partial\tau}{w(\tau)/w^*(\tau)} = g_y - g_y^* > 0,$$

Consider the effect of a rise in the rate of productivity growth in both sectors of the backward economy by the constant proportion $\vartheta > 1$, so that $g_y' = \vartheta . g_y$. It follows immediately from the above that $\frac{\partial w(\tau)/w^*(\tau)/\partial\tau}{w(\tau)/w^*(\tau)}$ must rise. □

Proof of (ii): From equation (7.27), intertemporal utility in the advanced economy is given by,

$$U^*_{\tau_1} = \int_{\tau_1}^{\infty} e^{-\rho(\tau-\tau_1)}. \left[\beta.e^{(g_z-g_y+g^*_y)(\tau-\tau_1)}.\frac{A_z(\tau_1)}{A_y(\tau_1)}A^*_y(\tau_1)\right]^{\beta} . \left[(1-\beta).e^{g^*_y(\tau-\tau_1)}.A^*_y(\tau)\right]^{1-\beta},$$

$$U^*_{\tau_1} = \frac{\left[\beta.A_z(\tau_1)/A_y(\tau_1).A^*_y(\tau_1)\right]^{\beta} . \left[(1-\beta).A^*_y(\tau)\right]^{1-\beta}}{\rho - g^*_y - \beta.(g_z - g_y)},$$

Consider the effect of a rise in the rate of productivity growth in both sectors of the backward economy by the constant proportion $\vartheta > 1$, so that $g'_y = \vartheta.g_y$ and $g'_z = \vartheta.g_z$. Then it follows immediately from the above that intertemporal welfare may either rise or fall depending upon whether $g_z > g_y$ or $g_z < g_y$. □

Chapter 8

Conclusion

This thesis has argued that technological progress is an important determinant of an economy's rate of growth, and that the rate of technological progress is largely determined by the intentional choices of profit-seeking agents. Any endogenous growth model satisfying both criteria was termed *Schumpeterian*, and the analysis has sought to explain variations in growth rates across countries and across time within an endogenous growth framework.

Chapter 2 distinguished two main classes of Schumpeterian models: the variety-based approach of Romer (1990) and the "quality ladder" model of Aghion and Howitt (1992). In both models, the economy's long-run rate of growth is determined by profit-seeking investments in Research and Development (R & D). However, the vertical differentiation of technologies in the "quality ladder" approach means that each innovation renders obsolete existing techniques and destroys the flow of profits enjoyed by incumbent producers (*value obsolescence*). It seems plausible that growth is, as argued by Schumpeter (1942), a process of *creative destruction*, and much of the present analysis has been undertaken within the "quality ladder" approach.

Chapter 3 augmented a version of the basic "quality ladder" framework with a model of human capital accumulation. Considerable evidence exists that both human capital accumulation and Research and Development (R & D) are important for an economy's growth rate, and this was indeed the case within the endogenous growth model of Chapter 3. In addition, it was argued that the incentives to invest in human capital acquisition and Research and Development (R & D) are interdependent. Strategic complementarities between the two forms of investment, together with indivisibilities in the R & D technology, were found to be responsible for multiple equilibria for intermediate parameter values. One of these equilibria was interpreted as the "low skills" equilibrium, described in empirical work by Finegold and Soskice (1988). Equilibrium selection was dependent entirely upon agents' expectations, and as a result a welfare improving role for government policy in co-ordinating expectations existed for intermediate parameter values.

In Chapters 2 and 3, as in most existing models of endogenous growth, it was assumed that the full productive potential of an innovation could be realised costlessly and instantaneously. In contrast, Chapter 4 considered the idea that the productive potential of an innovation might be realised only after a gradual process of further development. The existing endogenous growth literature with this feature was surveyed. Then, following Aghion and Howitt (1996a), a distinction was drawn between *fundamental innovations* ("major breakthroughs," e.g. the steam engine) and the *secondary innovations* (incremental improvements, e.g. the boring mill) that realise the opportunities latent in each fundamental discovery. Technological change becomes at least two-dimensional, as the productivity of each fundamental technology is augmented by a sequence of secondary innovations.

In Chapter 5, this distinction between fundamental and secondary innovation was applied to consider the circumstances under which there might be a "penalty" to being a pioneer of a technology. This idea has a long parentage in the economic history literature, and provides an alternative explanation for income convergence to those suggested in the existing literature. It seems plausible that many secondary innovations will be specific to the fundamental technology under which they were made, and hence that each fundamental innovation will induce *secondary knowledge obsolescence.* Such knowledge obsolescence constitutes another example of the way in which growth is essentially a process of creative destruction. More importantly, it means that the large stock of accumulated secondary knowledge implied by pioneer status may reduce an economy's incentive to invest in Research and Development (R & D) directed at the discovery of the next fundamental technology.

This reduced incentive to devote resources to fundamental research may in turn translate into a lower average rate of growth, although it was found to be implausible that it would reduce economic welfare. If the stock of accumulated secondary knowledge became sufficiently large, it was established that economy might devote no resources at all to fundamental research and become *locked-into* an existing technology. Although secondary knowledge obsolescence was found to reduce an economy's incentive to engage in fundamental research and potentially its rate of economic growth, this effect was offset by *secondary knowledge spillovers* in both the *research* and *production* sectors. If sufficiently large, these spillovers might be responsible for there being an "advantage to an early start."

In each of Chapters 2 to 5 the analysis was undertaken in the context of a closed economy. Chapter 6 turned to consider the relationship between rates of technological progress and international trade. In models of endogenous growth and trade, an economy's pattern of comparative advantage at any one point in time is *endogenously* determined by rates of productivity growth in each sector of the two economies. However, these rates of productivity growth themselves depend upon international specialisation, as determined by the current pattern of comparative advantage. Thus, the pattern of comparative advantage feeds back to determine its own evolution over time.

Chapter 6 argued that, in any dynamic trade model, a distinction exists between the traditional concept of comparative advantage used above (*static* comparative advantage (SCA)) and a second notion of *dynamic* comparative advantage (DCA). SCA is concerned with opportunity costs of production in the two economies, and determines the nature of international specialisation at a given point in time. In contrast, DCA is concerned with changes in opportunity costs of production, and determines the evolution of international specialisation over time. As such, DCA is related to an economy's ability to reallocate resources over time in each sector or the pattern of *intertemporal advantage* (IA).

Chapter 6 developed a dynamic Ricardian model of endogenous growth and trade, and proposed explicit definitions of dynamic comparative advantage (DCA) and intertemporal advantage (IA). It was argued that an economy might face a trade-off between specialising according to its current pattern of SCA and specialising in sectors where the potential for rapid productivity growth (as manifested in the patterns of IA and DCA) is capable of generating such an advantage in the future. Free trade, by inducing an economy to specialise according to its current pattern of SCA, may be welfare reducing. It was possible to derive necessary and sufficient conditions for free trade to be welfare reducing, and to relate these conditions to the concepts of DCA and IA defined above. In principle, protectionist measures to induce entry into sectors where an economy exhibits a potential DCA may be welfare improving, although the practical implementation of such policies would be fraught with difficulties.

Chapter 7 used the same dynamic Ricardian model to relate the analysis of the "penalty" to being a pioneer in Chapter 5 to an open economy setting. The nature of international specialisation and its evolution over time (as determined by the pattern of DCA) were found to be crucial for the evolution of the cross-section distribution of income. Income convergence and international leapfrogging depended upon specialisation being incomplete, and the initially backward economy having an intertemporal advantage (IA) in the sector where each economy was active. The "penalty" to being a pioneer was again found to provide an additional explanation for income convergence to those suggested in the existing literature.

Chapter 7 was also able to evaluate the claim that an economy's "international competitiveness" might be important for its standard of living and that a lack of such "competitiveness" could be an argument for protectionism. The claim that "international competitiveness" matters was interpreted as a claim about the level or rate of growth of aggregate productivity in one economy *relative* to that in another. So defined, the level of "international competitiveness" was found to be irrelevant to the existence of static gains from trade, which instead depend upon the pattern of *comparative* advantage. Furthermore, increases in a foreign economy's aggregate rate of productivity growth which reduce a home economy's "international competitiveness" were found to have an *ambiguous* effect upon the home economy's welfare. The home standard of living could either rise or fall depending upon whether such productivity growth was export- or import-biased.

Often, a concern about a lack of "international competitiveness" is associated with relative economic decline or income convergence. However, a rise in a backward economy's rate of productivity growth, that increases the rate of income convergence, was found to have an ambiguous effect upon the advanced economy's welfare, depending upon whether the increased productivity growth is export- or import-biased. The analysis of Chapter 6 suggested that a theoretical case for protectionist policies may exist. However, this case depends upon patterns of static and dynamic comparative advantage (relative levels and rates of productivity growth *in different sectors*) rather than on an aggregate notion of "international competitiveness."

In conclusion, the rate of technological progress is indeed an important determinant of an economy's rate of growth, and depends in large measure on the intentional investments of profit-seeking agents. The magnitude of entrepreneurs' investments in Research and Development (R & D) may well depend upon the size of workers' complementary investments in human capital accumulation, and the interdependence between these two forms of investment may generate multiple equilibria. Furthermore, the productive potential of an innovation may be only gradually realised through a process of further development, and this idea leads naturally to a distinction between fundamental and secondary innovation. This richer, two-dimensional model of technological change provides a natural explanation as to why there might be a penalty to being a pioneer of a technology or an advantage to having an early start. Finally, the analysis suggested that international trade interacts with the rate of technological progress in a such a way as to determine both the welfare effects of trade and the evolution of the cross-section distribution of income over time.

Bibliography

[1] Acemoglu Daron (1994) “Search in the Labor Market, Incomplete Contracts and Growth.” *CEPR Discussion Paper*, No. 1026, September

[2] Aghion Philippe and Howitt Peter (1992) ”A Model of Growth through Creative Destruction.” *Econometrica*, March, pp 323-351

[3] ——— (1994) “Growth and Unemployment.” *Review of Economic Studies*, vol. 61(3), pp. 477-494

[4] ——— (1996a) “Resarch and Development in the Growth Process.” *Journal of Economic Growth*, January

[5] ——— (1996b) *Notes On Endogenous Growth*, Nuffield College, Oxford, mimeo

[6] Aghion Philippe, Dewatripont Mathias and Rey Patrick (1995) “Competition, Financial Discipline and Growth.” Nuffield College Oxford, mimeo

[7] Aghion Philippe, Harris Christopher and Vickers John (1995) “Competition and Growth with Step-by-Step Technological Progress.” Nuffield College, Oxford, mimeo

[8] Amable Bruno (1993) “Radical and Incremental Innovation: A model of Endogenous and Unsteady Growth.” CEPREMAP, mimeo

[9] Amsden Alice H (1989) *Asia’s Next Giant: South Korea and Late Industrialisation*, Oxford University Press, New York

[10] Arrow Kenneth J (1962) “The Economic Implications of Learning by Doing.” *Review of Economic Studies*, pp 155-73

[11] Arthur Brian (1989) "Competing Technologies, Increasing Returns and Lock-in by Historical Events." *Economic Journal*, March, pp 116-131

[12] Aspin Chris (1981) *The Cotton Industry*, Shire Publications Ltd., Princes Risborough, Aylesbury, U.K.

[13] d'Autume Antoine and Michel Philippe (1993) "Endogenous Growth in Arrow's Learning by Doing Model." *European Economic Review*, vol. 37, pp. 1175-1184

[14] Azariadis Costas and Drazen Allan (1990) "Threshold Externalities in Economic Development." *Quarterly Journal of Economics*, pp. 501-526

[15] Backus David, Kehoe Patrick and Kehoe Timothy (1992) "In Search of Scale Effects in Trade and Growth." *Journal of Economic Theory*, vol. 58, pp. 377-409

[16] Bahk Byong-Hyong and Gort Michael (1993) "Decomposing Learning by Doing in New Plants." *Journal of Political Economy*, vol. 101, no. 4, pp. 561-583

[17] Barro Robert J and Sala-i-Martin Xavier (1991) "Convergence Across States and Regions." *Brookings Papers on Economic Activity*, vol. 1, pp. 107-158

[18] ——— (1992) "Convergence." *Journal of Political Economy*, vol. 100, no. 2, pp. 223-251

[19] ——— (1995a) *Economic Growth*, McGraw-Hill, New York

[20] ——— (1995b) "Technological Diffusion, Convergence and Growth." *NBER Working Paper*, No. 5151, June

[21] Bartel Ann P and Lichtenberg Frank R (1987) "The Comparative Advantage of Educated Workers in Implementing New Technology." *The Review of Economics and Statistics*, vol. 69, pp. 1-11

[22] Baumol W J (1986) "Productivity Growth, Convergence and Welfare: What the Long-run Data Show." *American Economic Review*, vol. 76, pp. 1072-1085

[23] Beath John, Katsoulacos Yannis and Ulph David (1989) "The Game-Theoretic Analysis of Innovation: A Survey." *Bulletin of Economic Research*, vol. 41, no. 3, pp. 163-184

[24] Ben-David Dan and Papell David H (1995) "The Great Wars, The Great Crash and Steady-state Growth: Some New Evidence About an Old Stylised Fact." *Sackler Institute for Economic Studies*, Tel-Aviv University, Working Paper No. 36-95, November

[25] Benhabib Jess and Spiegel Mark M (1994) "The role of Human Capital in Economic Development: Evidence from Aggregate Cross-Country data." *Journal of Monetary Economics*, vol. 34, pp. 143-173

[26] Bhagwati J N (1982) "Directly Unproductive Profit-Seeking (DUP) Activities." *Journal of Political Economy*, vol. 90, pp. 988-1002

[27] Bliss Christopher (1995) "Capital Mobility, Convergence Clubs and Long-Run Economic Growth." *Nuffield College Discussion Paper*, No. 100, August

[28] Blundell R, Griffith R and Van Reenan J (1995) "Dynamic Count Data Models of Technological Innovation." *Economic Journal*, March, pp. 333-344

[29] Bresnahan T and Trajtenberg M (1992) "General Purpose Technologies: Engines of Growth ?" *NBER Working Paper* No. 4148

[30] Brezis Elise S, Krugman Paul R, and Tsiddon Daniel (1993) "Leapfrogging in International Competition: A Theory of Cycles in National Technological Leadership." *American Economic Review*, December, pp 1211-1219

[31] Bulow Jeremy, Geanakoplos John and Klemperer Paul (1985) "Multimarket Oligopoly: Strategic Substitutes and Complements." *Journal of Political Economy*, vol. 93, no. 3

[32] Caballero Ricardo J and Jaffe Adam B (1993) "How High are the Giants Shoulders: An Empirical Assessment of Knowledge Spillovers and Creative Destruction in a Model of Economic Growth." *NBER Working Paper*, No. 4370

[33] Cameron Gavin (1996a) "Innovation and Economic Growth." *CEP Discussion Paper*, No. 277, February

[34] _____ (1996b) "Catch-up and Leapfrog Between the USA and Japan." Nuffield College, Oxford, mimeo

[35] Caselli Francesco, Esquivel Gerardo and Lefort Fernando (1995) "Reopening the Convergence Debate: A New Look at Cross-Country Growth Empirics." Paper presented at the Seventh World Congress of the Econometric Society, Tokyo

[36] Cass David (1965) "Optimum Growth in an Aggregative Model of Capital Accumulation." *Review of Economic Studies*, vol. 32, pp. 233-240

[37] Coe David T and Helpman Elhanan (1993) "International R & D Spillovers." *CEPR Discussion Paper*, No. 840

[38] Cooper Russell and John Andrew (1988) "Co-ordinating Co-ordination Failures in Keynesian Models." *Quarterly Journal of Economics*, vol. 103, pp. 441-463

[39] Crafts Nicholas F (1996) "Endogenous Growth: Lessons For and From Economic History." *CEPR Discussion Paper*, No. 1333, January

[40] David Paul (1985) "Clio and the Economics of QWERTY." *American Economic Review*, May, vol. 75, pp 332-337

[41] Dornbusch R, Fischer S and Samuelson P (1977) "Comparative Advantage, Trade and Payments in a Ricardian Model with a Continuum of Goods." *American Economic Review*, December, pp. 823-839

[42] Dosi Giovanni (1982) "Technological Paradigms and Technological Trajectories." *Research Policy*, 11, pp 147-162

[43] Durlauf S N and Johnson P A (1995) "Multiple Regimes and Cross-Country Growth Behaviour." *Journal of Applied Econometrics*, vol. 10, pp. 365-384

[44] Easterly W, Kremer M, Pritchett L and Summers L H (1993) "Good Policy or Good Luck ? Country Growth Performance and Temporary Shocks." *Journal of Monetary Economics*, vol. 32, pp. 459-483

[45] Enos John L and Park W H (1988) *The Adoption and Diffusion of Imported Technology: The Case of Korea*, Routlege, London

[46] Finegold David and Soskice David (1988) "The Failure of Training in Britain: Analysis and Prescription." *Oxford Review of Economic Policy*, vol. 4, no. 3, pp. 21-53

[47] Foster Andrew D and Rosenzweig Mark R (1995) "Learning by Doing and Learning From Others: Human Capital and Technical Change in Agriculture." *Journal of Political Economy*, vol. 103, no. 6, pp. 1176-1209

[48] Frankel, Marvin (1955) "Obsolescence and Technical Change in a Maturing Economy." *American Economic Review*, vol. XLV, no. 3, June, pp 296-319

[49] Friedman Milton (1992) "Do Old Fallacies Ever Die ?" *Journal of Economic Literature*, pp. 2129-2132

[50] Fudenberg D, Gilbert R, Stiglitz J and Tirole J (1983) "Pre-emption, Leapfrogging and Competition in Patent Races." *European Economic Review*, vol. 22, pp. 3-31

[51] García-Peñalosa Cecilia (1995) "Absolute Poverty or Relative Inequality: A Theory of Growth and Wage Differentials." *Nuffield College Discussion Paper*, No. 97, May

[52] Griliches Zvi (1980) "Returns to R & D Expenditures in the Private Sector." in (eds.) Kendrick K and Vaccara B, *New Developments in Productivity Measurement*, Chicago University Press, Chicago

[53] Grossman Gene M (1990) "Explaining Japan's Innovation and Trade: A Model of Quality Competition and Dynamic Comparative Advantage." *NBER Working Paper*, No. 3194

[54] Grossman Gene M and Helpman Elhanan (1990) "Comparative Advantage and Long-run Growth." *American Economic Review*, vol. 80, no. 4, pp. 796-815

[55] ——— (1991a) *Innovation and Growth in the Global Economy.* MIT

[56] ——— (1991b) "Quality Ladders in the Theory of Growth." *Review of Economic Studies*, pp 43-61

[57] Halpern L (1995) "Comparative Advantage and the Likely Trade Pattern of the C.E.E.C.s." in (eds) R Faini and R Portes, *European Union and Trade with Eastern Europe*, CEPR, London

[58] Harris C and Vickers J (1985) "Perfect Equilibrium in a Model of a Race." *Review of Economic Studies*, vol. 52, pp. 193-209

[59] Helpman Elhanan and Trajtenberg Manuel (1994) "A Time to Sow and a Time to Reap: Growth Based on General Purpose Technologies." *NBER Working Paper*, No. 4854, September

[60] Hicks J R (1953) "An Inaugral Lecture." *Oxford Economic Papers* (New Series), June

[61] Islam Nazrul (1995) "Growth Empirics: A Panel Data Approach." *Quarterly Journal of Economics*, November, pp. 1127-1170

[62] Jenkins Helen (1995) "Education and Production in the United Kingdom." *Nuffield College Discussion Paper*, No. 101, August

[63] Johnson H G (1955) "Economic Expansion and International Trade." *Manchester School of Economic and Social Studies*, vol. 23, May, pp. 95-112

[64] Jones Charles I (1995a) "Time Series Tests of Endogenous Growth Models." *Quarterly Journal of Economics*, pp. 495-525

[65] ——— (1995b) "R & D-Based Models of Economic Growth." *Journal of Political Economy*, vol. 103, no. 4, pp. 759-784

[66] Jones Larry E and Manuelli Rodolfo E (1990) "A Convex Model of Equilibrium Growth: Theory and Policy Implications." *Journal of Political Economy*, vol. 98, no. 5, pp. 1008-1038

[67] Jorgenson D W and Fraumeni B M (1992) "Investment in Education and U.S. Economic Growth." *Scandanavian Journal of Economics*, vol. 94, pp. 51-70

[68] Jovanovic Boyan and Nyarko Yaw (1994) "The Bayesian Foundations of Learning by Doing." New York University, mimeo

[69] Jovanovic Boyan and Rob Rafael (1990) "Long Waves and Short Waves: Growth Through Intensive and Extensive Search." *Econometrica*, vol. 58, November, pp. 1391-1409

[70] Keep Ewart and Mayhew Ken (1988) "The Assessment: Education, Training and Economic Performance." *Oxford Review of Economic Policy*, vol. 4, no. 3, pp. i-xv

[71] Kindleberger C P (1961) "Obsolescence and Technical Change." *Oxford University Institute of Statistics Bulletin*, August, pp 281-97

[72] Koopmans Tjalling (1965) "On the Concept of Optimum Economic Growth." *The Econometric Approach to Development Planning*, Amsterdam, North Holland

[73] Kremer Michael (1993) "Population Growth and Technological Change: One Million B.C. to 1990." *Quarterly Journal of Economics*, pp. 681-716

[74] Krugman Paul (1981) "Trade, Accumulation and Uneven Development." *Journal of Development Economics*, vol. 8, pp. 149-161

[75] ——— (1987) "The Narrow Moving Band, the Dutch Disease, and the Competitive Consequences of Mrs Thatcher: Notes on Trade in the Presence of Dynamic Scale Economies." *Journal of Development Economics*, vol. 27, pp. 41-55

[76] ——— (1994a) *Peddling Prosperity: Economic Sense and Nonsense in the Age of Diminished Expectations*, Norton, New York

[77] ——— (1994b) "Competitiveness: A Dangerous Obsession." *Foreign Affairs*, March/April, pp. 28-44

[78] ——— (1994c) "Does Third World Growth Hurt First World Prosperity ?" *Harvard Business Review*, July-August, pp. 113-121

[79] ——— (1995a) "Real Men Don't Eat Quiche." *Worldlink*, September/October, pp. 47-49

[80] ——— (1995b) "Growing World Trade: Causes and Consequences." *Brookings Papers on Economic Activity*, pp. 327-377

[81] Krugman Paul and Lawrence R (1994) "Trade, Jobs and Wages." *Scientific American*, April, pp. 44-49

[82] Krugman Paul and Obstfeld Maurice (1994) *International Economics*, Third Edition

[83] Lawrence Robert Z and Slaughter Matthew J (1993) "Trade and U.S. Wages: Giant Sucking Sound or Small Hiccup." *Brookings Papers on Economic Activity*, Microeconomics 2, pp. 161-210

[84] Leamer Edward E (1994) "Trade, Wages and Revolving Door Ideas." *NBER Working Paper*, No. 4716, April

[85] Lichtenberg S (1992) "R & D Investment and International Productivity Differences." *NBER Working Paper*, No. 4161, September

[86] Lucas Robert E (1988) "On the Mechanics of Economic Development." *Journal of Monetary Economics*, vol. 22, pp 3-22

[87] ——— (1993) "Making a Miracle." *Econometrica*, March, pp 251-72

[88] Maddison Angus M (1995) *Monitoring the World Economy 1820-1992*, Paris: OECD

[89] ——— (1996) "Macroeconomic Accounts for European Countries." in (eds) Van Ark B and Crafts N F, *Quantitative Aspects of Postwar European Economic Growth*, Cambridge, Cambridge University Press

[90] Mankiw N, Romer D and Weil D (1992) "A Contribution to the Empirics of Economic Growth." *Quarterly Journal of Economics*, May, pp 407-437

[91] Matsuyama Kiminori (1992) "Agricultural Productivity, Comparative Advantage and Economic Growth." *Journal of Economic Theory*, vol. 58, pp. 317-334

[92] Mokyr Joel (1990) *The Lever of Riches: Technological Creativity and Economic Progress*, Oxford University Press, New York

[93] Motta Massimo and Thisse Jacques-François (1955) "On the Persistence of Leadership or Leapfrogging in International Trade." *CEPR Discussion Paper*, No. 1106, January

[94] Mowery David and Rosenberg Nathan (1989) *Technology and the Pursuit of Economic Growth*, Cambridge University Press

[95] Nelson Richard R and Norman Victor D (1977) "Technological Change and Factor Mix over the Product Cycle: A Model of Dynamic Comparative Advantage." *Journal of Development Economics*, vol. 4, pp. 3-24

[96] Newton Isaac (1675) *Letter to Robert Hook*, February 5th

[97] Nickell Stephen (1994) "Competition and Corporate Performance." Institute of Economics and Statistics, Oxford, mimeo

[98] Nickell Stephen and Bell Brian (1995) "The Collapse in Demand for the Unskilled and Unemployment across the OECD." *Oxford Review of Economic Policy*, vol. 11, no. 1, pp. 40-62

[99] Nonneman Walter and Vanhoudt Patrick (1996) "A Further Augmentation of the Solow Model and the Empirics of Economic Growth for OECD Countries." Forthcoming, *Quarterly Journal of Economics*

[100] Olson Mancur (1982) *The rise and decline of nations: economic growth, stagflation and social rigidities.* Yale University Press

[101] Parente Stephen L (1994) "Technology Adoption, Learning by Doing and Economic Growth." *Journal of Economic Theory*, pp. 346-369

[102] Parente Stephen L and Prescott Edward C (1994) "Barriers to Technology Adoption and Development." *Journal of Political Economy*, vol. 102, no. 2, pp. 298-321

[103] Patel P and Soete L (1988) "L'évaluation des effets économiques de la technologie." *STI Review*, no. 4, pp. 133-183

[104] Quah Danny (1993a) "Galton's Fallacy and the Convergence Hypothesis." *Scandanavian Journal of Economics*, vol. 95, pp. 427-443

[105] ——— (1993b) "Empirical Cross-Section Dynamics in Economic Growth." *European Economic Review*, vol. 37, pp. 426-434

[106] ——— (1996a) "Empirics for Economic Growth and Convergence." *European Economic Review*, vol. 40, Forthcoming

[107] ——— (1996b) "Convergence Empirics Across Economies with (Some) Capital Mobility." *Journal of Economic Growth*, vol. 1, March, pp. 95-124

[108] ——— (1996c) "Ideas Determining Convergence Clubs." LSE Economics Department, mimeo

[109] Ramsey Frank P (1928) "A Mathematical Theory of Saving." *Economic Journal*, vol. 38, pp. 543-559

[110] Rapping Leonard A (1965) "Learning and World War II Production Functions." *Review of Economics and Statistics*, vol. 47, pp. 81-86

[111] Rebelo Sergio (1991) "Long run Policy Analysis and Long run Growth." *Journal of Political Economy*, vol. 99, no. 3, pp 500-521

[112] Redding Stephen J (1994) "Innovation and Growth." Unpublished M. Phil. Thesis, University of Oxford

[113] ——— (1996a) "The Low-Skill, Low-Quality Trap: Strategic Complementarities Between Human Capital and R & D." Forthcoming, *Economic Journal*

[114] ——— (1996b) "Economic Miracles and the Low-Level Development Trap." Nuffield College, Oxford, mimeo

[115] ——— (1996c) "A Reconsideration of the Infant-Industry Argument." Nuffield College, Oxford, mimeo

[116] Ricardo David (1817) *On the Principles of Political Economy and Taxation*, London, John Murray, Albemarle Street

[117] Rivera-Batiz Luis and Romer Paul (1991a) "International Trade with Endogenous Technological Change." *European Economic Review*, vol. 35, pp. 971-1004

[118] ——— (1991b) "Economic Integration and Endogenous Growth." *Quarterly Journal of Economics*, pp. 531-555

[119] Romer Paul M (1986) "Increasing Returns and Long-Run Growth." *Journal of Political Economy*, vol. 94, no. 5, pp. 1002-1037

[120] ——— (1987) "Growth based upon increasing returns due to specialisation." *American Economic Review*, vol. 77, Papers and Proceedings, pp 56-62

[121] ——— (1990) "Endogenous Technical Change." *Journal of Political Economy*, vol 98, no. 5, §71-102

[122] ——— (1993) "Ideas and Things." *The Economist*, 150 Economist Years, pp 86-90

[123] Sala-í-Martin Xavier (1994) "Regional Cohesion: Evidence and Theories of Regional Growth and Convergence." *CEPR Discussion Paper*, No. 1075, November

[124] Schmookler Jacob (1966) *Invention and Economic Growth*, Harvard University Press, Cambridge, Mass.

[125] Schumpeter Joseph (1942) *Capitalism, Socialism and Democracy.* Harper: New York

[126] Searle Allan D (1945) "Productivity Changes in Selected Wartime Shipbuilding Programs." *Monthly Labour Review*, vol. 61, pp 1132-47

[127] Segerstrom Paul S, Anant T C A and Dinopoulos Elias (1990) "A Schumpeterian Model of the Product Lifecycle." *American Economic Review*, vol. 80, pp 1077-91

[128] Shaked A and Sutton J (1984) "Natural Oligopolies and International Trade." in (ed) Kierzkowski H, *Monopolistic Competition and International Trade*, Oxford, Oxford University Press

[129] Shell K (1966) "Toward a Theory of Inventive Activity and Capital Accumulation." *American Economic Review*, Papers and Proceedings, pp. 62-68

[130] Snower Dennis J (1994) "The Low-Skill, Bad-Job Trap." *CEPR Discussion Paper*, No. 999, September

[131] Södersten Bo and Reed Geoffrey (1994) *International Economics*, Third Edition

[132] Solow Robert M (1956) "A Contribution to the Theory of Economic Growth." *Quarterly Journal of Economics*, vol. 70, pp 65-94

[133] ——— (1957) "Technical Change and the Aggregate Production Function." *Review of Economics and Statistics*, vol. 31, pp 312-20

[134] Steedman Hilary and Wagner Karin (1989) "Productivity, Machinery and Skills: Clothing Manufacture in Britain and Germany." *National Institute Economic Review*, May, pp. 40-57

[135] Stokey Nancy L (1988) "Learning by Doing and the Introduction of New Goods." *Journal of Political Economy*, vol. 96, pp 701-17

[136] ——— (1991) "Human Capital, Product Quality and Growth." *Quarterly Journal of Economics*, May, pp. 587-616

[137] Summers Robert and Heston Alan (1988) "A New Set of International Comparisons of Real Product and Prices: Estimates for 130 Countries." *Review of Income and Wealth*, vol. 34, pp. 1-25

[138] Swan T W (1956) "Economic Growth and Capital Accumulation." *Economic Record*, vol. 32, pp. 334-361

[139] Taylor Scott M (1991) "Quality Ladders and Ricardian Trade." *Journal of International Economics*, vol. 34, pp. 225-243

[140] ——— (1994) "Once-off and Continuing Gains from Trade." *Review of Economic Studies*, vol. 61, pp. 589-601

[141] Temple Jon (1996) "Testing Schumpeterian Growth Theory." Nuffield College, Oxford, mimeo

[142] Temple Jon and Johnson Paul (1996) "Social Capability and Economic Development." Nuffield College, Oxford, mimeo

[143] Thurow Lester C (1992) *Head to Head: The Coming Economic Battle among Japan, Europe and America*, New York: Morrow

[144] Tirole Jean (1988) *The Theory of Industrial Organisation*, MIT

[145] Tyson Laura D'Andrea (1992) *Who's Bashing Whom: Trade Conflict in High-Technology Industries*, Washington: Institute for International Economics

[146] Ulph A M and Ulph D T (1994) "Labour Markets and Innovation: Ex-post Bargaining." *European Economic Review*, vol. 38, pp. 195-210

[147] Veblen Thornstein (1915) *Imperial Germany and the Industrial Revolution*, Macmillan: New York

[148] Wang Z and Winters L A (1994) *Eastern Europe's International Trade*

[149] Wood Adrian (1994) *North-South Trade, Employment and Inequality: Changing Fortunes in a Skill-Driven World*, Clarendon Press, Oxford

[150] Worldlink (1995) *The Magazine of the World Economic Forum*, September/October

[151] Wright T P (1936) "Factors Affecting the Cost of Airplanes." *Journal of the Aeronautical Sciences*, vol. 3, pp. 122-128

[152] Young Alwyn (1991) "Learning by Doing and the Dynamic Effects of International Trade." *Quarterly Journal of Economics*, vol. 106, pp 369-406

[153] ——— (1993a) "Invention and Bounded Learning by Doing." *Journal of Political Economy*, no. 3, pp 443-472

[154] ——— (1993b) "Substitution and Complementarity in Endogenous Innovation." *Quarterly Journal of Economics*, August, pp 775-807

[155] ——— (1995) "Growth Without Scale Effects." *NBER Working Paper*, No. 5211, August

2 Notation for Chapter 2

2.2 Exogenous versus Endogenous Growth

All lower case letters denote per capita variables.

Symbol	*Meaning*
τ	Time
Y	Final goods output
$G(\cdot)$	Production function
A	Stock of technological knowledge
K	Stock of physical capital
L	Supply of unskilled labour
$F(\cdot)$	Production function
α	Elasticity of final goods output with respect to physical capital
s	Savings rate
g	Exogenous rate of technological progress
η, B	Technological parameters

2.3 Variety and Growth

The notation is exactly the same as that in Section 2.2, except in the following cases.

Symbol	*Meaning*
H	Supply of Skilled Labour
$x(j)$	Flow of output of intermediate input $j \in [0, A]$
α	Elasticity of final goods output with respect to skilled labour
β	Elasticity of final goods output with respect to unskilled labour
η	Number of units of final goods output required to produce one

	unit of any durable intermediate input
U_τ	Intertemporal utility evaluated at time τ
ρ	Subjective rate of time preference
c_τ	Representative agent's consumption of the final good at time τ
C_τ	Aggregate consumption at time τ
r_τ	Interest rate
$1/\sigma$	Intertemporal elasticity of substitution
λ	Productivity of research
ξ	Steady-state rate of growth

2.5 Quality and Growth

The notation is exactly the same as that in Section 2.3, except in the following cases.

Symbol	*Meaning*
x	Flow of intermediate goods output
α	Elasticity of final goods output with respect to the output of intermediate inputs
$A_m = \gamma^m.A_0$,	Quality of intermediate inputs at time τ
$m = 0, 1, ..., M$	Interval beginning with m^{th} innovation (or with $t = 0$ in the case of $m = 0$) and ending just before the $m + 1^{st}$. Hence, m indexes the state of the art technology at time τ
$\gamma > 1$	Size of innovations
$p^y_\tau = 1$ for all τ	Price of final goods output
H^x	Aggregate flow of skilled labour devoted to intermediate input production
H^r	Aggregate flow of skilled labour devoted to Research and Development (R & D)
λ	Productivity of research
ι	Instantaneous probability of innovation

V_m	Value of m^{th} innovation
p^x	Price of intermediate inputs
π	Instantaneous flow of profit from intermediate input production
w	Skilled wage
$\omega = w_m/A_m$	Productivity-adjusted wage
$MC(H^r_m)$	Marginal Cost of research
$MB(H^r_{m+1})$	Marginal Benefit of research
$\psi : H^r_{m+1} \rightarrow H^r_m$	Research employment this period is a decreasing function of research employment next period
ζ	Equilibrium average rate of growth of final goods output

2.6 Extensions and Qualifications

The notation is exactly the same as that in Section 2.5, except in the following cases.

Symbol	*Meaning*
$q \in (-\infty, M_\tau)$	Quality of intermediate inputs
σ	Elasticity of substitution between qualities of intermediate inputs
μ	Rate of diffusion of innovations
β	Rate of "knowledge obsolescence"
δ	The "size" of knowledge spillovers from a given cohort of ideas
ϕ	The exponent on the stock of existing technological knowledge in the equation for accumulating technological knowledge

3 Notation for Chapter 3

Symbol	*Meaning*
τ	Time
t	Generation
$j = 1, 2$	Each generation lives for two periods j
l	Indexes individual workers $l \in [0, L]$
i	Indexes individual entrepreneurs $i \in [0, N]$
$U_t(\cdot)$	Lifetime utility of a worker of generation t
$c_{j,t}$	Final goods consumption of generation t in period $j = 1, 2$
ρ	Subjective rate of time preference
r	Interest rate
$h_{j,t}(l)$	Period j human capital of a worker l in generation t
H	Aggregate or economy-wide stock of human capital
$\delta \in (0, 1)$	Rate of "depreciation" of human capital across generations
$\nu(l) \in [0, 1]$	Fraction of period 1 devoted to education or human capital accumulation by worker l
η	Productivity of education parameter
θ	Elasticity of period 2 human capital with respect to the fraction of period 1 devoted to education
$y_{j,t}(i)$	Period j flow of final goods output produced by entrepreneur i of generation t
$Y_{j,t}$	Aggregate period j flow of final goods output in generation t
$A_{j,t}(i)$	Period j productivity or quality of the technology employed by entrepreneur i of generation t
$p_{t,j} = 1$ for all t, j	Price of final goods output
$\alpha(i) \in [0, 1]$	Fraction of period 1 output devoted to Research and Development (R & D) by entrepreneur i
$\lambda \in (0, 1)$	Productivity of research parameter
$\mu(i) \in [0, 1)$	Probability that entrepreneur i innovates at the end of

	period 1
$\gamma > 1$	Size of innovations
$m = 0, 1, ..., M$	Interval beginning with m^{th} innovation (or with $t = 0$ in the case of $m = 0$) and ending just before the $m + 1^{st}$. Hence, m indexes the state of the art technology at time τ
$w_{j,t}(i)$	Period j wage received by an employee of entrepreneur i in generation t
$W_{j,t}(i)$	Period j flow of income received by an employee of entrepreneur i in generation t
$\beta \in (0,1)$	Fraction of surplus from final goods production received by workers
E	Expectations operator
$V_e^R(i)$	Entrepreneur i's expected return from investing in Research and Development (R & D)
$V_e^0(i)$	Entrepreneur i's expected return from not investing in Research and Development (R & D)
$\Omega(l)$	Worker l's return from devoting a fraction $\nu(l)$ of period 1 to education
ξ_t	Expected rate of growth of final goods output between periods 1 and 2 of generation t
s	R & D subsidy
$\phi \in (0,1)$	Proportional rate of tax on entrepreneurs' profits

4 Notation for Chapter 4

Symbol	*Meaning*
τ	Time
G	Cumulative gross investment
$\eta(\cdot)$	Quantity of labour required to produce a unit of output with a given capital good
b, α	Technological parameters

$m \in [0, M(\tau)]$,	Indexes the degree of technological sophistication of goods, with the production of higher numbered goods involving more advanced technologies
$M(\tau)$	Denotes the most sophisticated good that society knows how to produce at time τ
H	Constant mass of skilled labour
$\bar{a}(m)$	*Potential* unit labour requirements for good m
$a(m, \tau)$	Actual unit labour requirements for good m at time τ
$N(\tau)$	The most sophisticated good for which all potential for learning by doing has been exhausted at time τ
$H^p(m, \tau)$	Flow of skilled labour devoted to the production of good m at time τ
U_τ	Intertemporal utility at time τ
ρ	Subjective rate of time preference
$c(m, \tau)$	Consumption of good m at time τ
$y(m, \tau)$	Output of good m at time τ
$p(m, \tau)$	Price of good m at time τ
w	Skilled wage
$\underline{m}(\tau)$	Least sophisticated good consumed in equilibrium at time τ
$\bar{m}(\tau)$	Most sophisticated good consumed in equilibrium at time τ
H^r	Flow of skilled labour employed in research
$a_r > 0$	Productivity of research parameter
$u\{c(\cdot, \tau)\}$	Utility functional
$g(\cdot)$	Sub-utility functional
$E(\tau)$	Expenditure
$r(\tau)$	Interest rate in the riskless consumption loans market
$l \in [0, L]$	Unskilled labour
Y	Aggregate output of an homogeneous final good
A_τ	Stock of general knowledge at time τ
v	Vintage of a fundamental line
$Y_{\tau,v}$	Final goods output from a fundamental line of vintage v at time $\tau \geq v$

$S_{\tau,v}$	Number of intermediate inputs developed for lines of vintage v by time $\tau \geq v$
$A_v.B(l_{\tau,v})$	Flow of final goods output from an intermediate input on a fundamental line of vintage v at time $\tau \geq v$
H^d_τ	Aggregate flow of skilled labour employed in development at time τ
λ^r	Poisson arrival rate of fundamental innovations for each researcher
H^r_τ	Aggregate flow of skilled labour employed in research at time τ
σ	Exogenous rate of upgrading for secondary developers
h^d_τ	Flow of skilled labour entering the development of lines of the most recent vintage at time τ
η_τ	Flow of skilled labour entering the development of *each* line of the most recent vintage at time τ
$\lambda^d_\tau = \lambda^d.(\eta_\tau)^{-\mu}$	Poisson arrival rate of secondary innovations for each developer, where $0 < \mu < 1$
$\beta, (1-\beta)$	Weights with which fundamental and secondary innovations contribute to the growth of general knowledge
$\psi(\cdot)$	Function determining the rate of growth of general knowledge
g	Steady-state rate of growth
V^r	Expected present value of the income a researcher will receive over the (random) interval until his alternative choice as a developer is upgraded to a new line
V^d	Expected present value of the income a developer will receive over the (random) interval until she is upgraded to a new line
κ	Fraction of profits from developing a line that are received by a researcher
$1-\kappa$	Corresponding fraction received by skilled workers developing a line
W_τ	Expected present value of the rents generated by intermediate input production on each fundamental line opened at time τ

5 Notation for Chapter 5

Symbol	*Meaning*
τ	Time
t	Generation
$j = 1, 2$	Each generation lives for two periods j
H	Constant mass of consumer-producers in each generation t
$U_t(\cdot)$	Lifetime utility of a representative agent in generation t
$c_{j,t}$	Representative agent's period $j = 1, 2$ consumption of final goods output in generation t
ρ	Subjective rate of time preference
r	Interest rate
$Y_{j,t}$	Aggregate period j flow of final goods output in generation t
$F_{j,t}$	Stock of fundamental knowledge in period j of generation t
$S_{j,t}$	Stock of secondary knowledge in period j of generation t
ν	Elasticity of final goods output with respect to the stock of fundamental knowledge
x	Flow of intermediate goods output
α	Elasticity of final output with respect to the flow of output of intermediate inputs
$\gamma > 1$	Size of fundamental innovations
$\Theta \equiv F^{\nu}.S$	Index of the productivity / quality of intermediate inputs
$p(Y_{t,j}) = 1$ for all t, j	Price of final goods output
h_t	Number of individuals in generation t who choose to enter the production sector
n_t	Number of individuals engaged in fundamental research in generation t
ι	Probability that a fundamental innovation occurs at the end of period 1

$\lambda(\cdot)$	Productivity of research
$m = 0, 1, ..., M$	Interval beginning with m^{th} innovation (or with $t = 0$ in the case of $m = 0$) and ending just before the $m + 1^{st}$. Hence, m indexes the state of the art technology at time τ
g	Proportional rate of growth of secondary knowledge or the rate of learning by doing
$\mu \geq 0$	Learning by doing parameter
$\theta \in (0, 1)$	Secondary knowledge spillover parameter
$\sigma > 0$	Elasticity of final goods output produced using fundamental technology m with respect to the secondary knowledge acquired under technology $m - 1$
$\phi \in [1, +\infty)$	Indexes the number of generations since the discovery of the current state of the art fundamental technology m
$p_{j,t}(x_t)$	Price of intermediate inputs
$w_{j,t}$	Wage in the production sector during period j of generation t
$V_{x,t}$	Expected present discounted value of a lifetime spent in the production sector
$\pi_{j,t}$	Period j flow of profit from intermediate input production in generation t
$V_{r,t}$	Expected present discounted value of a lifetime spent undertaking research
$MC(n_t)$	Marginal Cost of entering the research sector
$MB(n_t)$	Marginal Benefit of entering the research sector
$\tilde{S}_{1,t}$	Critical value of the stock of accumulated secondary knowledge, above which technological lock-in occurs
E	Expectations operator
$\zeta_{t,t+1}$	Expected proportional rate of growth of final goods output between generations t and $t + 1$
$\bar{n}_{t+1}$	Generation $t + 1$ equilibrium research employment in the event that research is successful in generation t
$\underline{n}_{t+1}$	Generation $t + 1$ equilibrium research employment in the event that research is unsuccessful in generation t

$\varepsilon \in [0,1]$	Fraction of inherited stock of secondary knowledge "destroyed" by the social planner at the beginning of period 1
$\delta \in (0,1)$	Learning by doing parameter

6 Notation for Chapter 6

Symbol	*Meaning*
$*$	Denotes a foreign variable
Z	Aggregate flow of output of the low-technology, traditional good
Y	Aggregate flow of output of the high-technology, frontier good
z	Flow of output of the low-tech good produced by a representative individual in the low-tech sector
y	Flow of output of the high-tech good produced by a representative individual in the high-tech sector
$j = z, y$	Final goods sector (low-technology or high-technology)
$\bar{L}$	Mass of consumers and supply of skilled labour
τ	Time
U_τ	Intertemporal utility evaluated at time τ
ρ	Subjective rate of time preference
c_j	Representative individual's consumption of the output of sector j
C_j	Aggregate consumption of the output of sector j
$\beta, 1-\beta$	Elasticity of instantaneous utility with respect to consumption of low-tech and high-tech goods respectively
A_j	Productivity of skilled labour in sector j
L_j	Flow of skilled labour employed in sector $j = z, y$
K_j	Stock of cumulative production experience in each sector $j = z, y$
ψ_j	Exogenous determinants of productivity in each sector

	$j = z, y$
α_j, γ_j	Learning by doing parameters in each sector $j = z, y$ where learning by doing is bounded
g_j	Rate of learning by doing in each sector $j = z, y$ where learning by doing is unbounded
p_j	Price of final goods output in sector j
RD_z	World demand for the low-tech good relative to the high-tech good
C_j^W	World consumption of the output of sector j
w_j	Wage received from final goods production in sector j
RS_z	World supply of the low-tech good relative to the high-tech good
τ_1	Time $\tau > 0$ at which trade is opened between the two previously autarkic economies
F	Indexes a variable under free trade
N	Indexes a variable under autarky
$\frac{p_z(z(\tau),y^*(\tau))}{p_y(z(\tau),y^*(\tau))}$	Relative price of the low-tech good when home specialises in the low-tech sector and foreign in the high-tech
$\frac{p_z(z^*(\tau),y(\tau))}{p_y(z^*(\tau),y(\tau))}$	Relative price of the low-tech good when home specialises in the *high*-tech sector and foreign in the low-tech
$s > 0$	Production subsidy in the high-tech sector
$0 < \xi < 1$	Tax on wage income in each sector
S	Indexes a variable under the subsidy
$\phi_j(\tau)$	Fraction of period τ devoted to Research and Development (R & D) in sector $j = z, y$
γ_j	Productivity of R & D in sector $j = z, y$

7 Notation for Chapter 7

The notation in Chapter 7 is identical to that in Chapter 6, except in the following cases,

Symbol	*Meaning*
Ω	Income per capita in home *relative* to foreign
τ_2	Point in time $\tau > 0$ at which income per capita catches-up with the level in its initially more advanced counterpart
τ_3	Point in time $\tau > 0$ at which *overtaking* or *leapfrogging* occurs
ϕ	Interval of time until income per capita in the backward economy catches-up with the level in its initially more advanced counterpart
τ_R	Point in time $\tau > 0$ at which the initial pattern of static comparative advantage is reversed
$B_y(\cdot)$	Function determining productivity in the high-tech sector
$\vartheta > 1$	Proportionate increase in the rate of productivity growth in the backward economy