Essays on Technological Change and Economic Growth

A thesis submitted to The University of Manchester for the Degree of

Doctor of Philosophy

in the Faculty of Humanities

2017

Cheng Cheng

Department of Economics

School of Social Sciences
## Contents

1 Introduction 6

1.1 Technological change and wage inequality ............................. 9
1.2 Population and income growth ........................................... 13

2 Technological Change, Employment and Wages in the Global Economy 16

2.1 Introduction ................................................................. 16
2.2 The baseline model ......................................................... 30
   2.2.1 Households ......................................................... 32
   2.2.2 Firms ................................................................. 34
   2.2.3 Equilibrium ......................................................... 36
   2.2.4 Wage Inequality within One Country .............................. 38
   2.2.5 International Wage Inequalities .................................. 38
   2.2.6 Optimal Consumptions ............................................ 39
2.3 Simulation ................................................................. 40
   2.3.1 First derivatives of individual wages .............................. 41
   2.3.2 First derivatives of international wage inequalities ............ 43
2.4 Analysis of Wage Inequalities ......................................... 45
   2.4.1 The effect of productivity enhancing technological change on individual wages ..................................... 45
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4.2</td>
<td>The effect of transportation cost reducing technological change on individual wages</td>
<td>47</td>
</tr>
<tr>
<td>2.4.3</td>
<td>The effect of productivity enhancing technological change on domestic wage inequality</td>
<td>49</td>
</tr>
<tr>
<td>2.4.4</td>
<td>The effect of transportation cost reducing technological change on domestic wage inequality</td>
<td>51</td>
</tr>
<tr>
<td>2.4.5</td>
<td>The effect of productivity enhancing technological change on international wage inequality</td>
<td>53</td>
</tr>
<tr>
<td>2.4.6</td>
<td>The effect of transportation cost reducing technological change on international wage inequality</td>
<td>54</td>
</tr>
<tr>
<td>2.5</td>
<td>Conclusions</td>
<td>55</td>
</tr>
</tbody>
</table>

3 Population Growth and Technological Change

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>61</td>
</tr>
<tr>
<td>3.2</td>
<td>The Model</td>
<td>68</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Households</td>
<td>70</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Firms</td>
<td>73</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Market equilibrium</td>
<td>80</td>
</tr>
<tr>
<td>3.3</td>
<td>Dynamics of Human Capital, Population, Technology and per capita Wage Incomes</td>
<td>81</td>
</tr>
<tr>
<td>3.3.1</td>
<td>Dynamics of human capital and population</td>
<td>81</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Dynamics of two types of technology</td>
<td>84</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Dynamics of per capita wage incomes</td>
<td>88</td>
</tr>
<tr>
<td>3.4</td>
<td>Conclusions</td>
<td>92</td>
</tr>
<tr>
<td>3.5</td>
<td>Appendix</td>
<td>93</td>
</tr>
<tr>
<td>3.5.1</td>
<td>The Malthusian Regime</td>
<td>94</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>3.5.2 The Post Malthusian Regime</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>3.5.3 The Modern Growth Regime</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td>4 Conclusion</td>
<td>119</td>
<td></td>
</tr>
</tbody>
</table>
Abstract

This thesis places the role of technological change at the centre and provides two theoretical frameworks to explain the impact of technological change not only on wage inequalities within and across countries but also on the historical evolution in population, human capital and income per capita.

Chapter 2 presents a general equilibrium model that is able to explain both domestic and international wage inequalities. The main argument is that there are broadly two types of technological change: productivity enhancing technological change and transportation cost reducing technological change. The former increases labour productivity in the country where such technological change is invented. The latter reduces transportation costs internationally, which lowers the price for imported goods thereby increasing the demand. This paper incorporates these two types of technological change into an open trade economy, where, we assume, there are two countries (i.e. home and foreign) and each country has two types of labour (i.e. skilled and unskilled). The results show that the wage inequality within one country is determined by its own combination between two types of technological change. Both skilled and unskilled international wage inequalities between two countries are determined by the combination of two technological changes in two countries.

Chapter 3 considers a unified overlapping generations model to account for the dynamic evolution in technological progress, population growth, the growth in income per capita and human capital accumulation from pre-modern to modern days, by distinguishing two types of technological change: experience-based technological change and experiment-based technological change. The former is invented mainly based on past experiences gained from, for example, production or investment, which is mostly unintentional. By contrast, the latter is generated by investing both physical and human capital and is normally intentional. Our model argues
that the key to explain such dynamic evolution depends on which type of technological change predominates across different periods.
Declaration

I declare that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
Copyright Statement

The author of this thesis (including any appendices and/or schedules to this thesis) owns any copyright in it (the “Copyright”) and s/he has given The University of Manchester the right to use such Copyright for any administrative, promotional, educational and/or teaching purposes.

Copies of this thesis, either in full or in extracts, may be made only in accordance with the regulations of the John Rylands University Library of Manchester. Details of these regulations may be obtained from the Librarian. This page must form part of any such copies made.

The ownership of any patents, designs, trade marks and any and all other intellectual property rights except for the Copyright (the “Intellectual Property Rights”) and any reproductions of copyright works, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property Rights and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property Rights and/or Reproductions.

Further information on the conditions under which disclosure, publication and exploitation of this thesis, the Copyright and any Intellectual Property Rights and/or Reproductions described in it may take place is available from the Head of School of Social Sciences or the Vice-President.
Acknowledgments

I would like to express my great appreciation to my supervisor Dr. Xiaobing Wang for his guidance and insightful suggestions in shaping the overall theme of my research. He has given me a lot of generous support and encouragement during my research.

The Department of Economics at Manchester has provided a happy and stimulating environment for the completion of the thesis. I would like to thank the leaders of the PhD programme, Professor Horst Zank, Dr. Kyriakos Neanidis and Dr. Alejandro Saporiti for their support and professional facilitation throughout my PhD study. I would like to thank Dr. Matias Cortes for evaluating my PhD progression and support. In addition, many staffs and fellow students at the department have helped me in various ways throughout the programme.

I would also like to acknowledge the financial support provided by the Department of Economics at the University of Manchester in the form of scholarship and awards allowing me to pursue the doctoral programme in Economics at the University of Manchester.

Last but not least, a very special thanks to my parents, whose trust and encouragement have enabled me to do my work.
Chapter 1

Introduction

Data on earnings and wages reveals that there has been a large increase in the wage difference between skilled (i.e. workers with higher levels of ability, education and/or training) and unskilled workers across both developed and developing economies since the 1970s. This indicates that the ratio of skilled to unskilled wages, which is also known as the skill premium, has been an increasing trend in a large number of both developed and developing countries in the world (excluding certain East Asian countries). Due to the monetary incentives for skilled labour, an increasing number of workers have upgraded their skills by improved education. During the period between the 1970s and the mid-1990s, the quantity of college-educated workers nearly doubled in the United States, until now the proportion of such workers in the workforce have significantly increased. This increasing supply of skilled labour with college education, especially during the 1980s, accompanied the increase in skill premium. This suggests that there also existed an increase in the demand for skilled labour. A similar trend of widening wage gap also happened among other developed and developing countries. The increase in wage inequality has always been a great concern among economists. Many of them have attempted to interpret the wage inequality between skilled and unskilled labour within one country (e.g. the United States).

Although the global income inequality is high, the wage inequality of workers with the
same skill level but in different countries has not been well investigated. Due to data limitations, global income inequality is analyzed according to gross domestic product (GDP) per capita. The recent data regarding the comparable earning across countries is not always available. However, the study for cross-country wage inequality in terms of workers from different countries but with the same skill level is still meaningful. This is due to the following reasons.

Firstly, such study can distinguish the causes of global wage inequality. Specifically, the difference in average earnings for workers across various countries can be caused by either the difference in average skill levels or the difference in returns to skill or even both. If the global wage inequality is mainly affected by the variations in average skill levels, such inequality would be reduced by increasing skill levels. Nevertheless, if variations in returns to skill across different countries lead to such wage inequality, the way of reducing this inequality would be different. For instance, according to the labour force surveys regarding occupational wages, there were substantial differences in wage for a construction carpenter during 1995. The wage for a construction carpenter was $42 per month in India. Workers with the same job were paid $125 per month in Mexico, $1,113 per month in Korea and $2,299 per month in the United States. However, based on these numbers, it is limited to differentiate the proportion of wage differentials caused by variations in skill levels and the proportion because of changes in returns to skill in different countries.

Secondly, the analysis on cross-country wage inequality for workers with the same skill helps to understand the fact of international labour migration. Difference in wage payments for a given skill across countries plays a major role in analyzing the gains through labour migration, and this in turn affects both the choice and quantity of global migration. For instance, if the cross-country wage inequality for construction carpenters between the United States and India is mainly caused by differences in returns to skill rather than skill levels, a construction carpenter in India would have the motivation to migrate, and vice versa. However, existing literature has
not adopted the data regarding the cross-country wage difference when analyzing the global migration. Most of these studies considered the variations in GDP per capita across countries and other variables to investigate migration. Difference in cross-country GDP per capita is affected by the variations in the quantity of human capital, population level and the labor force participation, etc. Thus, GDP per capita is not quite representative when analyzing migration decisions.

Lastly, the cross-country wage inequality shows the efficiency in terms of global labour allocation. Higher international wage difference indicates higher misallocation in both international labour and, sometimes, other possible factors of production. This would therefore negatively affect the aggregate income level in the world, which would be significantly lower compared with the case with efficient cross-country labour allocation. For instance, if workers with a given skill receive low wage in some developing countries relative to the wage paid for the same skill level in certain developed countries (i.e. the international wage inequality with a given skill is high), the number of people who have the same skill ability in the developing country would move to the developed country, which would increase the level of global migration and hence reduce the international wage inequality (Rosenzweig, 2010).

In addition to the rising wage inequalities both domestically and internationally, population growth is another major global issue today since it has a direct impact on economic growth. Throughout most of human history, changes in both technological development and population growth were extremely small compared with modern growth. Technological progress only led to a higher population level, however, income per capita remained almost stationary (i.e. Malthusian Stagnation). Nevertheless, during the 1800s, there existed an obvious and substantial increase in the growth of technological development together with industrialization. The Malthusian Trap therefore was no longer in existence in many countries and the growth rates of both population and income per capita increased substantially. Although technological
development during the pre-Industrial Revolution period was not able to create stable economic
growth, as more human capital was required in production during the second phase of industrial-
alization, this led to the demographic transition, which eventually reduced population growth
rate while both technological progress and human capital accumulation continued increasing.
This resulted in the emergence of persistent economic growth in modern times.

The interpretation of such entire evolution has always been regarded as one of the most
challenging projects facing economists. Existing studies have tried to explain this evolution
through different mechanisms. In particular, technological change has been considered as one of
the most influential factors accounting for such historical evolution. There are different types of
technological change generated from various mechanisms and this may provide different effects
on the growth in population, human capital and income per capita. Nevertheless, existing
studies treat the process of technological change as homogeneous while interpreting the entire
evolution, and different processes of technological invention have not been identified among
these studies.

This thesis contributes to the existing literature on both wage inequality and population
growth. In chapter 2, we take the importance of global wage inequality into consideration and
hence provide a general equilibrium model to account for both domestic and international wage
inequalities, with a special emphasis on the role of technological change. In chapter 3, we firstly
distinguish two types of technological change based on existing endogenous growth theories.
Within our unified overlapping generations framework, we then examine the impact of these
on the dynamic evolution in technological change, population, human capital and income per
capita.

1.1 Technological change and wage inequality

The interaction between technological change and the labour market has always been
regarded as one of many issues for economists, which has lasted for as long as economics was viewed as a independent area of study. In particular, the study on the impact of technological change on wage inequality has been increasing all the time. Many studies have shown the increase in wage inequality within the United States, which was due to technological change, for example, microcomputers (e.g., Bound and Johnson 1992, Levy and Murnane 1992, Katz and Murphy 1992, Juhn, Murphy and Pierce 1993). Katz (1999) showed that wage inequality started to increase during the beginning of the 1980s after the discovery of microcomputers. In addition, Krueger (1993) provided that the more skilled (i.e. more highly educated) the workers, the more likely they will use computers. This implies that computers are complementary with skilled workers (i.e. human capital). These observations were also confirmed by other literature (e.g., Johnson 1997). Eventually, the idea, that technological change leads to an increase in the demand for skilled labour and hence in wage inequality, has been named as the skill biased technological change hypothesis, and such hypothesis has been widely accepted and adopted by recent literature while analyzing wage inequality within one country (e.g., Acemoglu 2002, Willem te Velde 2003, Acemoglu and Autor 2010, Dabla-Norris, Kochhar, Ricka, Suphaphiphat, and Tsounta 2015).

Acemoglu (2002) considered that the skill biased technological change had resulted in an increase in wage inequality within the US during the twentieth century. This idea was further analyzed by Acemoglu and Autor (2010) who also stated that technological change had a negative impact on labour replaced by machinery in the US. Recent study investigated by Dabla-Norris, Kochhar, Ricka, Suphaphiphat, and Tsounta (2015) also confirmed the idea of skill biased technological change, where income inequality between low skilled and high skilled labour increased in larger emerging market economies, despite a significant rise in the supply of highly educated workers. Willem te Velde (2003) argued that the skill biased technological change could be caused by foreign direct investment, which had resulted in an increase in skilled
labour relative to unskilled.

However, the hypothesis of skill biased technological change is not able to explain the fact that wage inequality was stabilized during the 1990s, even though there existed ongoing technological change in computers. This led to a reconsideration of the role of skill biased technological change. The pioneers of this were Autor, Levy and Murnane, and they introduced a new hypothesis of routinization-biased technological change which substituted workers in both routine manual and cognitive tasks and complemented workers in non-routine cognitive tasks. They argued that this type of technological change had resulted in a rise in the relative demand of highly educated graduates from the 1970s, which provided a new explanation for wage inequality in the US (Autor, Levy and Murnane, 2003). This result was also reflected in Autor, Katz, and Kearney (2006), where information technology affected the task demands leading to the recent wage polarization in the US. Following this, other literature has adopted this new hypothesis of technological change to explain the wage structure in the UK and other countries within Europe (e.g., Goos and Manning 2007, Goos, Manning and Salomons 2009). Goos and Manning (2007) argued that both high skilled and low skilled employment volumes increased whilst the level of the middle skilled decreased in the UK since 1975. This job polarization was consistent with the hypothesis of routinization-biased technological change, which could not be explained by skill biased technological change. Goos, Manning and Salomons (2009) also adopted the idea of routine-biased technological change to explain job polarization in Europe from the early 1990s.

The existing studies have mainly focused on analyzing the impact of technological change on wage inequality within one country throughout different periods. However, the area considering the effect of technological change on global wage inequality for a certain skill level has largely been neglected. Moreover, the hypotheses of both skill-biased and routinization-biased technological changes are not able to account for such inequality. This is due to the fact that
international wage inequalities are not only affected by the productivity of a country but also the transport costs between countries through the Balassa-Samuelson effect.

Therefore, motivated by these limitations, chapter 2 provides three main contributions to the existing literature. Our first contribution is to introduce a new theory by distinguishing two types of technological change, which provides explanations for both domestic and international wage inequalities. The first type is called the productivity enhancing technological change which increases the productivity for skilled labour in the country where such technological change is invented. The second is known as the transportation cost reducing technological change, which reduces transportation costs between countries, thereby reducing the price for imported products and hence increasing the demand. Our division of technological change is based on the existing facts regarding the impact of technological change on both labour productivity and transportation costs. The second contribution is to identify the source of the reduction in trade costs, particularly the transportation costs. Existing studies have regarded the shock reducing trade costs as exogenous (e.g., Dix-Carneiro and Kovak 2015, Aado 2015, Burstein and Vogel 2016). However, we consider that technological change plays an important part in determining such reduction, which is based on existing facts regarding the impact of technological change on transportation costs. The last contribution is to consider the impact of technological change on wage inequality of workers with the same/similar level of skills but in different countries. We provide a simple general equilibrium model in an open economy environment, which is able to account for both domestic and international wage inequalities. Within this framework, our analysis places the role of two different technological changes at the centre, and we find that changes in the predominance between the two technological changes have a significant impact on determining wage inequalities both domestically and internationally.
1.2 Population and income growth

One of the oldest challenges in economics is to provide an explanation for the interaction between income and population throughout entire human history. Prior to 1800, there existed a gradual growth in population while income per capita in world economies was almost stable. Around the Industrial Revolution, population growth started to accelerate together with income per capita. In modern times, population growth rate started to decline while the growth in income per capita continues to increase together with human capital accumulation.

Many studies have tried to explain these facts. The evolution in both population and income per capita in the early stages of development was well explained by the Malthusian theory, where technological change only favoured the level of population in the long term whilst income per capita remained almost unchanged. However, the Malthusian theory is limited to explain the facts that both population and income per capita increased as development progressed and that there is a negative relationship between population growth and the growth in income per capita during modern times. Many studies have, in the main, targeted the changes in both population and income during modern times (e.g., Becker 1960, Becker and Lewis 1973, Barro and Becker 1989, Galor and Weil 1996, Iyigun 2000, Blackburn and Cipriani 2002, Lord and Rangazas 2006, Bhattacharya and Chakraborty 2012, Varvarigos and Zakaria 2013). For example, Becker (1960) and Becker and Lewis (1973) argued that there was a trade-off between the quality and quantity of children, and the substitution of quality for quantity was caused by the increase in the relative return of child quality (i.e. education). The idea of such trade-off was also confirmed by Barro and Becker (1989).

But despite this, the following influential studies have provided models explaining the entire evolution in population and income. For instance, Becker et al. (1990) developed a framework capturing various regimes regarding the relationship between income and fertility
rates, with a special emphasis on the negative effect of an increase in the return to human capital on reducing the number of children. Tamura (1996), Galor and Weil (2000), Lagerlf (2003) and Strulik and Weisdorf (2008) gave more sophisticated explanations for the evolution in population and income covering the entire human history. Some of these studies have analyzed the impact of technological change on the historical evolution in both population and income growth (e.g., Galor and Weil 2000). However, technological change was considered only from the aggregate point of view and existing theoretical frameworks were silent on the ways that technological changes were invented.

Motivated by this, chapter 3 contributes to the existing literature in the following two ways. Firstly, we distinguish two types of technological change based on two different ways of inventing technology. Our technological division is based on the endogenous growth theories, which has not previously been well categorized within this field. Secondly, an existing study investigated by Galor and Weil (2000) considered the impact of technological change on the evolution in population growth and income per capita. However, they neglected various types of technological change and only considered the impact of total technological change on such evolution. Motivated by this, according to our categorization of two technological changes based on endogenous growth theory, our research digs into this deeper and shows that these two types of technological change have various impacts on the evolution in population growth, growth in human capital and growth in income per capita, which provides a complementary theory to Galor and Weil (2000). Mathematically, we incorporate these two types of technological change into a unified overlapping generations framework that generates dynamics in population growth, growth in human capital and growth in wage income per capita from prehistoric times to the present day. Our results reveal that gradual transition from experience-based to experiment-based technological change plays a fundamental role in determining such dynamics, which are generally consistent with relevant facts.
The rest of the thesis is organized as follows. Chapter 2 considers the role of various technological changes in an open economy environment and focuses on analyzing their impact on both domestic and international wage inequalities. Chapter 3 investigates the effect of different technological changes on the growth of population, human capital and income per capita. The conclusion together with some guidance regarding potential research for future studies are provided in the last chapter.
Chapter 2

Technological Change, Employment and Wages in the Global Economy

2.1 Introduction

There have already been intensive studies investigating the impact of technological change on wage inequality. These studies have mainly considered the role of the skill-biased technological change and routinization biased technological change in interpreting the wage inequality within just one country (e.g., Acemoglu 2002, Autor, Levy, and Murnane 2003). The effect of technological change on international wage inequality has not been well researched. In this paper, we propose two types of technological change in a general equilibrium model, and capture the effect of these two technological changes on domestic as well as international wage inequality.

In the past two centuries, there has been a significant increase in wage inequality within one country (e.g., Acemoglu 2002, Acemoglu and Autor, 2010), and many studies have investigated this from different perspectives. The skill biased technological change, which complements the skilled workers and substitutes the unskilled workers, has been widely thought to have important implications on the increase in wage inequality. For example, Acemoglu (2002) argued that skill biased technical change had led to a rise in wage inequality within the US during the
twentieth century, and more significantly, the increase in wage inequality from 1970 was caused by the acceleration in the skill biased technical change. Acemoglu and Autor (2010) argued that it was more likely that the technological change, which replaced some tasks performed manually before with new machines, negatively affected the earnings and employment of the labour force who were replaced by machinery in the US.

The idea of skill biased technological change was also confirmed in Dabla-Norris, Kochhar, Ricka, Suphaphiphat, and Tsounta (2015), where, for example, although the supply of highly educated workers in larger emerging market economies increased significantly, there existed an increase in income inequality between low skilled and high skilled labour. Across OECD countries, almost a third of rising income difference (i.e. the comparison between workers in the 10th and workers in the 90th percentile) could be explained by technological changes during the past 25 years (OECD, 2011). Moreover, foreign direct investment may have stimulated skill biased technological change, leading to an increase in skilled labour relative to the unskilled (Willem te Velde, 2003).

However, the growth of wage inequality in the US had slowed down in the latter part of the twentieth century (Card and DiNardo, 2002 and Lemieux, 2006). These results led to questioning the ability of the skill biased technological change in interpreting wage inequality. Autor, Levy and Murnane (2003) reconsidered the role of technological change in interpreting wage structure and introduced the concept of routinization-biased technical change. They focused on analyzing the impact of computerization, which substituted workers in both routine manual and cognitive tasks and complemented workers in non-routine cognitive tasks, on wage structure within a country. This routinization-biased technical change caused an increase in the relative demand of highly educated graduates during the last three decades, and influenced the growth of wage inequality in the US.

Goos and Manning (2007) showed that non-routine jobs included both the high skilled
and the low skilled jobs, whilst routine jobs were mostly middle skilled. According to Goos and Manning (2007), the employment share of the high skilled and the low skilled increased, but the share of the middle skilled jobs decreased since 1975 in the UK. Furthermore, they argued that this job polarization could not be well interpreted by the skill biased technical change classification. Instead, they argued that the routinization-biased technical change hypothesis was consistent with job polarization and also accounted for changes in both the upper tail and lower tail wage inequality in the UK. Apart from the UK, job polarization was also found to exist in other developed countries, like the US. For instance, Autor, Katz, and Kearney (2006) supported the routinization-biased technical change hypothesis and concluded that changes in information technology (computerization) resulted in a change in task demands and hence had an impact on the recent wage polarization in the US. Goos, Manning and Salomons (2009) showed that the routine-biased technological change explained job polarization starting from the early 1990s in Europe.

According to these existing studies to date, there has been intensive work concerning the impact of technological change on wage differentials and employment levels within a country. In particular, both skill-biased and routinization-biased technological changes have been well regarded as the driving forces to explain the variations in domestic wage structure in different periods. However, these classifications make it difficult to shed light on international wage inequality, since this is not only affected by the productivity of a country but also the transport costs between countries through the BalassaSamuelson effect.

In this paper, we argue that there can be another division of technological change. Specifically, the major effects of technological changes are reflected either on improving labour productivity or on reducing transaction costs, especially transportation costs. Accordingly, this paper distinguishes two types of technological change: the productivity enhancing and the transportation cost reducing technological change. We apply them to analyze the role of technological
change in interpreting wage inequality both domestically and internationally. A change can be said to be productivity enhancing if it increases labour productivity, and can be regarded as transportation cost reducing technological change if it reduces the transportation cost (and more broadly transaction cost) in international trade.

Of course, the distinction of these two types of technological change does not mean that one excludes the other. Some of the technological changes that belong to one kind may also have impact on both productivity and transportation costs. However, even if they are not that distinctive in their impacts, we can argue that a proportion of it is productivity enhancing and a proportion is transportation cost reducing.

It is reasonable to distinguish these two types of technological change, as both have distinctive impacts on enhancing productivity and reducing transportation cost. The importance regarding the effect of the reduction in transportation cost caused by technological change on international trade has been widely accepted. Behar and Venables (2010) argued that technological change played a significant role in reducing transport costs and stimulating the volume of international trade. Hummels (2007) argued that technological change had a huge impact on reducing both international ocean and air transportation costs during recent decades. For example, technological change resulted in a massive reduction in shipping costs after the World War II period, which led to a significant increase in international trade. From a global point of view, technology mainly led to a decrease in transportation costs, an upgrade in both automation and communication during last four decades (Dabla-Norris, Kochhar, Ricka, Suphaphiphat, and Tsounta, 2015).

One of the most influential innovations is containerization, which adopts steel containers to transport products, and such containers are transferred using lorries, ships or trains. After World War II, transport costs were dramatically decreased because of containerization which had improved the efficiency in both transport and trade of goods and had made them cheaper.
For instance, since containers were quicker to load, this motivated the development of bigger ships loading more containers, which significantly cut the cost of such transport. Containerization favoured the boom in international trade during the post-war period and played a major role in globalization (Wikipedia). Levinson (2006) showed that the shipping container made the world smaller and the world economy bigger. Headrick (2009) analyzed that technological change in the twentieth century was mainly containerization which stimulated globalization. Bernhofen, El-Sahli and Kneller (2016) examined these claims by estimating the impact of containerization on world trade. They showed the evidence that containerization was a driver of globalization during the twentieth century and helped to increase international trade.

Many other studies have confirmed the fact that the reduction in international transportation costs has led to the increase in international trade. Harley (1980, 1988, 1989), North (1958, 1968) and Mohammed and Williamson (2004) reported the effect of technological change on the dramatic decrease in shipping costs during the period between 1850-1913. Estevadeordal et al (2003) empirically analyzed the interaction between the reduction in shipping costs and an increase in the growth of trade within the first era of globalization. Both the adoption of containerization in ocean shipping and the invention of jet aircraft engines also reflected the importance in technological change on shipping since World War II. Hummels (2007) stated that technological change had led to a significant decrease in air shipping costs from 1955 to 2004, resulting in an increase in air shipping, which contributed positively to both US imports and exports. In terms of ocean shipping, Hummels (2007) recognized that technological change had an impact on container shipping throughout the world. The reduction in shipping costs was caused by the rise in the amount of trade which was containerized.

Moreover, economic historians considered that the technological change in ocean shipping played a important role in bringing about an increase in trade during the first era of globalization (i.e. around the latter half of the 19th century). During the second era (i.e. around the
latter half of the 20th century), Hummels (2007) stated that both technological development in air shipping and the cost reduction in transit had an impact on trade growth. He also argued that recent international trade, due to fast growth in technological change (for example, the innovations in both telecommunications and internet), had a great effect on international integration. This helped to increase the trade in technology, outsourcing, and skilled labour migration. For example, due to the significant reduction in transportation cost caused by using the internet, a number of jobs, for instance, call centres, were moved to countries with a relatively cheap labour force.

The fact that technological change is able to reduce transportation costs resulted in an increase in international trade, as illustrated in figure 1. Many studies have adopted the idea of increasing international trade to explain income inequality. For instance, across developed countries, skill-biased technological change and offshoring were regarded as the reason to account for increasing skill premium (i.e. the wage ratio between skilled and unskilled labour) (Feenstra and Hanson, 1996, 1999, 2003). Any increase in trade may have various impacts on unskilled wages across developed economies, where the skill premium may increase, and the real wage of unskilled workers may rise due to the reduction in price of import goods (Munch and Skaksen, 2009). By contrast, a rise in trade also led to a reduction in income inequality within emerging markets and developing countries, where low skilled workers are abundant. This is due to the rise in demand for low skilled labour and hence their wages. Therefore, differences in both factor intensity and productivity in various countries and also the source of income either comes from capital or wages, together determine the effect of trade on inequality.

**Figure 1 The openness in trade**
Sources: IMF, International Financial Statistics; IMF, World Economic Outlook database; and IMF staff calculations.

Notes: Trade openness is measured by total imports and exports as a percentage of GDP.

In addition, a number of studies have investigated the effect of international trade on skill premium based on the Heckscher-Ohlin framework. This framework showed that international trade, caused by trade costs reduction, had moved factors of productions to the sectors with comparative advantage and had increased the return to certain factors used intensively in such sectors. In other words, if the comparative advantage of a country is in the skill-intensive sectors, international trade would increase the skill premium in these countries, and vice versa. However, Goldberg and Pavcnik (2007) pointed out that the Heckscher-Ohlin model was unable to explain the fact that a number of countries with comparative advantage in unskilled labour also experienced the increase in skill premium.

Burstein and Vogel (2016) extended the Ricardian international trade framework by adding their assumptions regarding the variation in skill intensity among firms, sectors and countries. They showed that the decrease in trade costs led to the shift of certain factors to a country’s sectors with comparative advantages. Therefore, for countries with comparative advantage in skill intensive sectors, the skill premium in these countries would rise, and vice versa. Moreover, Burstein and Vogel argued that the decrease in trade costs resulted in the movement of factors to skill-intensive producers within sectors, which would raise the skill premium across all countries. Empirically, nearly all countries, including those which are skill scarce, have ex-
experienced a rise in the skill premium. They emphasized the importance regarding the role of the decline in trade costs in determining the increase in the skill premium.

Among these existing studies regarding the effect of international trade due to a decrease in trade cost on skill premium, the reduction in trade costs is assumed to be affected by a given exogenous shock. With this in mind, many studies analyzed the impact of trade cost reduction on the wage difference between labour with various skill levels within different countries, for instance, the skill premium between the skilled and unskilled workers. Different from these existing studies, this chapter highlights the following two new aspects: we firstly take into consideration the fact that technological change has a great impact on the reduction in trade costs, especially in transportation cost, and accordingly, our model endogenize the reduction in transportation cost which is determined by technological change. Secondly, existing studies have not considered the impact of technological change on international wage inequality between workers with the same/similar skill level but in different countries. Our research therefore fills this gap by investigating the impact of technological change, which results in a decrease in transportation cost, on such international wage inequality as well as domestic wage inequality between workers with different skill levels.

When considering the impact of technological change on labour productivity, Martnez, Rodriguez and Torres (2008a) divided technological change into neutral and investment specific technological change. The specific technological change in the US was mainly related to the technological progress in information and communication technologies (ICT) between 1980 and 2004. They argued that neutral technological change interpreted 57% growth in labour productivity. Specific technological change affected the remaining part of labour productivity growth. Particularly, the ICT-specific technological change accounted for approximately 35% growth in the US labour productivity during the last decade.

Martnez, Rodriguez-Lpez and Torres (2008b) showed the importance of the impact of
different technological changes on labour productivity growth in Europe as well as in the US between 1980 and 2004. Specifically, the effect of ICT technological change on labour productivity growth was larger in the US and Denmark than in any other European countries. In addition, technology increased labour productivity significantly and was a key driver to increase the skill premium, which caused an increase in income inequality in OECD countries, as shown in figures 2 and 3. The explanation for this was that technological change led to an increase in the demand for both skilled workers and capital, relative to both low skilled and unskilled workers. This was done through the replacement of many tasks by automation, which required skill upgrading in order to obtain such new jobs (Card and Dinardo, 2002; Acemoglu, 1998).

**Figure 2 Use of Information and Communication Technology (ICT)**

![Figure 2: Use of Information and Communication Technology (ICT)](image)

Source: Organization of Economic Cooperation and Development

Notes: ICT capital services per hour worked, 1990=100

**Figure 3 Skill Premium in Selected Economies**

![Figure 3: Skill Premium in Selected Economies](image)

Source: Organization of Economic Cooperation and Development

Notes: Skill premium measures the relative earnings from employment after complet-
ing tertiary education compared to the earnings after completing upper-secondary and post-secondary non-tertiary education, where upper-secondary or post-secondary non-tertiary education is 100.

In addition, as for modeling analysis, there are very few papers that have developed theoretical models which investigate the impact of technological change on both domestic and international wage inequalities. Jung and Mercenier (2010) developed a theoretical model that was able to show that the routinization-biased technical change was consistent with empirical evidence in terms of job polarization and wage structure since the early 90s. However, their model did not take international wage inequalities into consideration.

This chapter fills the above gap by developing a general equilibrium model that is able to account for wage inequalities both domestically and internationally. We place the role of technological change at the centre and analyze the impact of two different types of technological change on such wage inequalities. Our analysis reveals that changes in such wage inequalities are affected by variations in the predominance between two types of technological change. This chapter therefore provides a complementary theory to the existing frameworks associated with either skill/unskill-biased or routinization-biased technical changes.

Specifically, we establish a general equilibrium model in an open trade economy environment. We assume that there are two countries in the world. One is a developed country (for example, the US) and the other one is a developing country (for example, China). The two countries are symmetric but they are heterogeneous in labour supply and technological level. Within each country, labour is categorized into two types (i.e. skilled and unskilled). The share of skilled labour to unskilled labour in the developed country is higher than in the developing country. Moreover, labour is immobile between two countries. This immobility together with our assumption of the heterogeneity in both labour supply and technological level between two countries imply that factor prices are different between two countries. For example, wage
payments for both skilled and unskilled workers in the developed country would be different from those in the developing country. In other words, labour immobility allows the difference in wage payment for workers with the same skill level but in different countries, even when there is no international transportation cost (i.e., the theory of factor price equalization does not hold in our framework).

The overall technological level in the developed country is more advanced than in the developing country. Within each country, there are two types of technological change (i.e., productivity enhancing technological change and transportation cost reducing technological change). According to their characteristics, the productivity enhancing technological change in each country increases labour productivity within the same country and the transportation cost reducing technological change reduces the transportation costs between the two countries.

Each country consists of both households and firms. Households purchase both domestic and imported products, which are imperfectly substitutable. Furthermore, according to our labour type categorization, each individual can be either skilled or unskilled. By contributing skilled or unskilled labour effort to the production within firms, each individual receives either skilled or unskilled wage payment. We assume that all individuals in both countries are employed (i.e., full employment) in the labour market, and the total supply for each type of labour is fixed in both countries. As for production, there is one final goods sector within each country. Firms in this sector employ both skilled and unskilled workers to produce final products, from which labour demand for each type is determined.

Within the general equilibrium structure, taking full account of interactions between households and firms, our target is to consider how technological change affects wage inequalities within each country and across different countries. This is done by firstly deriving the equilibrium wages for both skilled and unskilled workers in each country, which are determined by both the fixed total supply for each labour type and the relevant labour demand from firms.
We then consider the equilibrium level of both domestic and international wage inequalities, where domestic wage inequality is measured by the wage ratio of skilled labour to unskilled, and international wage inequalities are determined by the ratio of skilled/unskilled workers in different countries.

Our findings show that variations in domestic and international wage inequalities are determined by changes in the share between productivity enhancing technological change and transportation cost reducing technological change within one country and across different countries, respectively. Specifically, the domestic wage inequality, whether developed or not, is determined by the country’s own share between productivity enhancing and transportation cost reducing technological change, and the effect of such technological share on domestic wage inequality varies depending on whether productivity-enhancing technological change has a relatively stronger impact on increasing skilled or unskilled productivity. For instance, when the effect of productivity-enhancing technological change positively influences the productivity of skilled labour to a greater degree relative to the productivity of the unskilled, given the total level of technological change, an increase in the share of productivity enhancing technological change would result in an increase in the domestic wage inequality. By contrast, if the productivity of unskilled labour benefits more from such technological change compared with the skilled, given the total level of technological change, an increase in the share of productivity enhancing technological change would lead to a decrease in the wage inequality within one country. These results are in line with the existing principles of both “skill-biased technical change” and “unskill-biased technical change”.¹

Moreover, we also found that, given the total level of technological change, if the tech-

¹Skill-biased technical change improves the productivity of skilled workers compared with the unskilled, which increases the relative demand for skilled workers. Similarly, unskill-biased technical change relatively increases the productivity of unskilled workers and hence the demand for such workers compared with the skilled workers. These ideas can be referred to Acemoglu (2002a).
nological change is mainly used to reduce international transportation cost (i.e. a decrease in the share of productivity-enhancing technological change), and simultaneously, if the effect of productivity-enhancing technological change positively influences the productivity of skilled labour to a greater degree compared with the productivity of the unskilled, domestic wage inequality would reduce. In contrast, if the unskilled productivity benefits more from the productivity-enhancing technological change, given the total level of technological change, an increase in the share of transportation cost reducing technological change would lead to an increase in domestic wage inequality. These results, which consider the impact of transportation cost reducing technological change on domestic wage inequality, provide explanations for the following three existing facts: the reduction in trade cost leads to an increase in domestic wage inequality across developed countries (Feenstra and Hanson, 1996, 1999, 2003). A rise in trade also led to a decrease in wage inequality within developing countries, where low skilled workers are abundant (Munch and Skaksen, 2009). Moreover, some developing countries experienced the increase in domestic wage inequality (Goldberg and Pavcnik, 2007 and Burstein and Vogel, 2016).

In an open economy between two countries (i.e. one developed country and one developing country), international wage inequalities of workers with the same skill level but in different countries are determined by the share of productivity enhancing and transportation cost reducing technological change in both countries, and the impact of such technological share on international wage inequalities varies depending on whether productivity-enhancing technological change in both countries improves skilled or unskilled productivity. Specifically, if the productivity-enhancing technological change in both countries have a stronger impact on improving the productivity of skilled workers compared with the unskilled productivity, there would be a positive (negative) relationship between the share of productivity-enhancing technological change in the developed country and international wage inequality between skilled
(unskilled) workers in different countries. In addition, there would exist a positive (negative) relationship between the share of productivity-enhancing technological change in the developing country and international wage inequality between unskilled (skilled) workers in different countries.

By contrast, if the productivity-enhancing technological change in both countries relatively increases the productivity of unskilled workers compared with the skilled productivity, there would be a negative (positive) relationship between the share of productivity-enhancing technological change in the developed country and international wage inequality between skilled (unskilled) workers in different countries. Furthermore, there would exist a positive (negative) relationship between the share of productivity-enhancing technological change in the developing country and international wage inequality between skilled (unskilled) workers in different countries.

Our result regarding the impact of technological change on reducing international wage inequalities corresponds with the existing finding provided by Acemoglu, Gancia and Zilibotti (2015), where they argue that low cost of offshoring from developed to developing country could reduce international wage inequality between skilled workers (or between unskilled workers) in both countries. Nevertheless, Acemoglu, Gancia and Zilibotti have only considered the determinant of the reduction in international wage inequalities. Our analysis also considers the scenario regarding the effect of technological change on increasing in either international wage inequality between skilled workers or between unskilled workers in different countries.

Our research contributes to the relevant existing literature in the following ways. Firstly, we introduce a new categorization of total technological change (i.e. productivity enhancing technological change and transportation cost reducing technological change), which is based on empirical facts regarding the effect of technological change on both labour productivity and international transportation costs, and such categorization has not been distinguished from
relevant existing studies. Secondly, conventional trade literature considered that the trade cost reduction was caused by an exogenous shock. For example, recent studies investigated by Dix-Carneiro and Kovak (2015) and Adao (2015) considered the effect of a given trade shock on the variations in skill premium through various regions within one country. Burstein and Vogel (2016) analyzed the role of a given trade shock in determining the economy-wide skill premium across different countries. In this chapter, we decompose this exogenous shock to find out the cause of the reduction in trade costs. Thanks to adequate empirical evidence regarding the impact of technological change on various trade costs, especially transportation cost, we argue that part of the shock lowering transportation cost is endogenously determined by technological change (i.e. transportation cost reducing technological change). Our model incorporates this feature into the analysis considering the interaction between labour market and international trade. Finally, existing theoretical studies have focused on analyzing the impact of technological change on wage inequality within one country. However, the impact of technological change on international wage inequality of workers with same/similar skill levels but in different countries has not been well considered. Our research therefore provides a theoretical framework which is able to account for both domestic and international wage inequalities.

This chapter is organized as follows. Section 2.2 integrates both productivity enhancing and transportation cost reducing technological changes into one baseline model. Section 2.3 provides the simulation. Section 2.4 shows propositions together with proofs and discussions. Section 2.5 concludes.

2.2 The baseline model

The structure of the economy in our model is based on the following assumptions: there exists two countries, home and foreign (*). The home country is a developed country and the foreign country is a developing country. The two countries are symmetric but they are
heterogeneous in technological level and labour endowments. Specifically, there are two types of labour in each country, skilled labour, $H$, and unskilled labour, $L$. We assume that the share of skilled labour to unskilled labour in the home country is larger than in the foreign country (i.e. $\frac{H}{T} > \frac{H^*}{T^*}$). For simplicity, physical capital is not included in our set-up. Moreover, the total technological level in each country is given exogenously. The total technological level, $T$, in the home country is higher than in the foreign country (i.e. $T > T^*$). The total technology in each country can be categorized as either productivity enhancing technological change or transportation cost reducing technological change. The former increases productivity of both skilled and unskilled labour. The latter reduces transportation costs between the two countries.

There are finite number of households having identical preference within one country. Each household can be either skilled or unskilled, and accordingly, the source of income for each household comes from either the skilled or unskilled wage payment. In each country, households spend their wages on consuming both domestically-produced and foreign-produced goods. Moreover, they participate in the production within firms, and the total supply of each labour type is exogenous. For simplicity, there is no unemployment in our framework.

Each country contains one final goods sector, where firms in this sector are assumed to be monopolistically competitive. The production of final goods requires both skilled and unskilled workers. Moreover, firms within one country produce the same product but in different varieties, and the final goods produced by the two countries are assumed to be imperfectly substitutable. This guarantees that each household obtains the utility by purchasing both home-produced and foreign-produced goods.

---

2 Including physical capital will only complicate calculation without affecting our results.
2.2.1 Households

In the home country, each household gains utility through the consumptions of two types of product, which come from both domestically produced goods and foreign produced goods. For simplicity, the utility function is assumed to be in Cobb-Douglas form:

\[ U(C_D, C_F) = C_D^{\varepsilon} C_F^{1-\varepsilon} \]  

where \( \varepsilon \in (0, 1) \) is a parameter. \( C_D \) and \( C_F \) represent consumptions of home-produced goods and foreign-produced goods, respectively.

Each household faces the following budget constraint while purchasing both domestic and foreign products:

\[ I \geq P C_D + \tau^* P^* C_F \]  

where \( I \) represents each household’s income level in the home country, which comes from either the skilled wage, \( w_H \), or the unskilled wage, \( w_L \) (i.e. \( I = w_H \) if the household is a skilled worker or \( I = w_L \) if the household is a unskilled worker). The producer price of home produced good is denoted by \( P \). Additionally, \( \tau^* - 1 \), where \( \tau^* \in [1, \infty) \), is the iceberg transportation cost per unit from foreign country to home country. Because of the iceberg transportation cost, in the home country, the consumer price for imported foreign products is denoted by \( \tau^* P^* \), while the consumer price for the home produced goods remains the same as its producer price, \( P \). In our model, we normalize \( P \) to 1 for simplicity.

By maximizing the utility (i.e. equation (2.2.1)) subject to the budget constraint (i.e. equation (2.2.2)), for each type of household in the home country (i.e. skilled and unskilled), the consumption of both domestically produced goods and imported foreign produced goods
are given by:

\[ C_{DH} = w_H \varepsilon \]  \hspace{1cm} (2.2.3)

\[ C_{FH} = \frac{w_H(1 - \varepsilon)}{\tau^*P^*} \]  \hspace{1cm} (2.2.4)

\[ C_{DL} = w_L \varepsilon \]  \hspace{1cm} (2.2.5)

\[ C_{FL} = \frac{w_L(1 - \varepsilon)}{\tau^*P^*} \]  \hspace{1cm} (2.2.6)

where \( C_{DH} \) and \( C_{FH} \) represent the consumption demands from skilled labour for home produced goods and foreign produced goods, respectively. \( C_{DL} \) and \( C_{FL} \) denote the consumption demands from unskilled labour for such products.

Similarly, in the foreign country, each household’s utility and budget constraint follow the same pattern as shown in the home country. Accordingly, the utility function and budget constraint for each household are given as follows:

\[ U^*(C_{D}^*, C_{F}^*) = (C_{D}^*)^\varepsilon (C_{F}^*)^{1-\varepsilon}, \varepsilon \in (0, 1) \]  \hspace{1cm} (2.2.7)

\[ I^* \geq \tau P C_{D}^* + P^* C_{F}^* \]  \hspace{1cm} (2.2.8)

The optimization problem (i.e. by maximizing the utility given by equation (2.2.7) subject to the budget constraint given by equation (2.2.8)) leads to the following results:

\[ C_{DH}^* = \frac{w_H \varepsilon}{\tau} \]  \hspace{1cm} (2.2.9)

\[ C_{FH}^* = \frac{w_H(1 - \varepsilon)}{P^*} \]  \hspace{1cm} (2.2.10)
\[ C_{DL}^* = \frac{w^*_L \varepsilon}{\tau} \]  
\[ C_{FL}^* = \frac{w^*_L (1 - \varepsilon)}{P^*} \]  

2.2.2 Firms

The final goods sector in the home country

Firms are monopolistically competitive in this sector. Each firm employs both skilled and unskilled workers to produce final products. The form of production function in this sector is based on Acemoglu (2002a, 2002b).

\[ Y = \left\{ \gamma[(\delta T)^\alpha L]^\rho + (1 - \gamma)[(\delta T)^\beta H]^\rho \right\}^{\frac{1}{\rho}} \]  

where \( \rho \in (0, 1) \) and \( \rho = \frac{\sigma - 1}{\sigma} \). \( \sigma \in (1, \infty) \) is the elasticity of substitution between \( H \) and \( L \), where \( H \) and \( L \) are gross substitutes. In line with the assumption of monopolistic competition in the final goods sector, \( \mu \in (1, \infty) \) implies that the production function exhibits increasing returns to scale. \( \delta \in (0, 1) \) is the share of two different technological changes. \( \gamma \), where \( \gamma \in (0, 1) \) represents a distribution parameter which reflects the importance of two factors (i.e. \( H \) and \( L \)). The amount \( \delta T \) represents the productivity enhancing technological change, which increases the productivity of both skilled and unskilled labour. The amount \( (1 - \delta)T \) denotes the transportation cost reducing technological change, which reduces the transportation cost (i.e. \( \tau - 1 \)) between the home and foreign countries. Mathematically, such impact of transportation cost reducing technological change on international transportation cost is represented by the equation \( \tau - 1 = \frac{1}{(1 - \delta)T} \), which simply reveals that an increase in the share of transportation

---

3 The general form of production function in Acemoglu (2002a, 2002b) is given by \( Y = \left[ \gamma(A_L L)^\rho + (1 - \gamma)(A_H H)^\rho \right]^{\frac{1}{\rho}} \), where \( A_L \) and \( A_H \) represent factor-augmenting technology terms.

4 The elasticity of substitution is based on Acemoglu (2002a), where \( \sigma > 1 \) represents that skilled and unskilled workers are gross substitutes, and gross complements if \( \sigma < 1 \).
cost reducing technological change (i.e. \(1 - \delta)T\) would lead to a decrease in transportation cost from home to foreign country (i.e. \(\tau - 1\)).

Building on the existing form of the production function in Acemoglu (2002a,2002b), we add \(\alpha\) and \(\beta\), where \(\alpha, \beta \in (0,1)\), in order to capture the effect of productivity enhancing technological change on unskilled and skilled labour, respectively. Moreover, \(Y\) represents the total amount of final output. \(H\) and \(L\) denotes the total number of skilled and unskilled workers employed in this sector, respectively.

The profit-maximization problem in this sector is given by: \(\text{Max}\ [Y - w_L L - w_H H]\), with \(P\) (i.e. the price level of final output) normalized to one. \(w_L L\) and \(w_H H\) are the wage payments for unskilled and skilled labour, respectively. The optimality conditions are:

\[
w_L = \mu \{ \gamma [ (\delta T)^\alpha L]^\rho + (1 - \gamma) [ (\delta T)^\beta H]^\rho \} \frac{\rho - 1}{\rho} \gamma (\delta T)^\alpha L^{-1} \tag{2.2.14}
\]

and

\[
w_H = \mu \{ \gamma [ (\delta T)^\alpha L]^\rho + (1 - \gamma) [ (\delta T)^\beta H]^\rho \} \frac{\rho - 1}{\rho} (1 - \gamma)(\delta T)^\beta H^{-1} \tag{2.2.15}
\]

The final goods sector in the foreign country

Due to the symmetry between home and foreign country, the production function of the final goods sector in the foreign country shares the same pattern as in the home country.

\[
Y^\star = \{ \gamma [ (\delta T^\star)^\alpha L^\star]^\rho + (1 - \gamma) [ (\delta T^\star)^\beta H^\star]^\rho \} \frac{\rho - 1}{\rho} \gamma (\delta T^\star)^\alpha L^\star \tag{2.2.16}
\]

The wages of both unskilled and skilled labour are:

\[
w_L^\star = P^\star \mu \{ \gamma [ (\delta T^\star)^\alpha L^\star]^\rho + (1 - \gamma) [ (\delta T^\star)^\beta H^\star]^\rho \} \frac{\rho - 1}{\rho} \gamma (\delta T^\star)^\alpha (L^\star)^{-1} \tag{2.2.17}
\]
and

\[ w_H^* = P^* \mu \{ [\delta^* T^*]^\alpha L^*]^{\rho} + (1 - \gamma) [(\delta^* T^*)^\beta H^*]^{\rho} \}^{\frac{2}{\rho} - 1} (1 - \gamma) (\delta^* T^*)^{\beta \rho} H^{\rho - 1} \]  

(2.2.18)

2.2.3 Equilibrium

The factor market equilibrium

There are two factors of production in our model (i.e. skilled and unskilled labour). The skilled labour market equilibrium requires the total demand of skilled workers in the final goods sector is equal to the total supply of skilled workers from households. The total supply of skilled workers is exogenous by assumption. The demand function for skilled workers in the final goods sector is given by equation (2.2.15). Accordingly, the equilibrium wage for skilled workers is given as below:

\[ w_H = \mu \{ [\delta T]^\alpha L^\rho + (1 - \gamma) [(\delta T)^\beta H^\rho] \}^{\frac{2}{\rho} - 1} (1 - \gamma) (\delta T)^{\beta \rho} H^{\rho - 1} \]  

(2.2.19)

Similarly, the unskilled labour market equilibrium requires that the supply of unskilled labour from households, which is assumed to be exogenous, is equal to the demand from the final goods sector (i.e. equation (2.2.14)). This leads to the following result for the equilibrium wage of unskilled workers:

\[ w_L = \mu \{ [\delta T]^\alpha L^\rho + (1 - \gamma) [(\delta T)^\beta H^\rho] \}^{\frac{2}{\rho} - 1} \gamma (\delta T)^{\alpha \rho} L^{\rho - 1} \]  

(2.2.20)

By symmetry between two countries, the unskilled and skilled wages in the foreign country
are given as follows:

\[ w_L^* = P^* \mu \left\{ \gamma \left[ (\delta^* T^*)^a L^* \right]^\rho + (1 - \gamma) \left[ (\delta^* T^*)^b H^* \right]^\rho \right\} \frac{\rho - 1}{\rho} \gamma (\delta^* T^*)^a (L^*)^{\rho - 1} \]  
\[ (2.2.21) \]

and

\[ w_H^* = P^* \mu \left\{ \gamma \left[ (\delta^* T^*)^a L^* \right]^\rho + (1 - \gamma) \left[ (\delta^* T^*)^b H^* \right]^\rho \right\} \frac{\rho - 1}{\rho} (1 - \gamma) (\delta^* T^*)^b (H^*)^{\rho - 1} \]  
\[ (2.2.22) \]

The goods market equilibrium

In an open trade economic environment, the equilibrium in the final goods market requires that the total supply of final products in one country is equivalent to the total demand from both home and foreign countries. Therefore, in the home country, such equilibrium is represented by

\[ Y = HC_{DH} + LC_{DL} + H^* C_{DH}^* + L^* C_{DL}^* \]  
\[ (2.2.23) \]

and in the foreign country

\[ Y^* = HC_{FH} + LC_{FL} + H^* C_{FH}^* + L^* C_{FL}^* \]  
\[ (2.2.24) \]

By substituting equations (2.2.3), (2.2.5), (2.2.9), (2.2.11), (2.2.13), (2.2.19), (2.2.20), (2.2.21) and (2.2.22) into equation (2.2.23), we drive the equilibrium price level in the foreign country:

\[ P^* = \frac{\tau (1 - \epsilon \mu)}{\epsilon \mu} \left\{ \frac{\gamma \left[ (\delta T)^a L \right]^\rho + (1 - \gamma) \left[ (\delta T)^b H \right]^\rho}{\gamma \left[ (\delta^* T^*)^a L^* \right]^\rho + (1 - \gamma) \left[ (\delta^* T^*)^b H^* \right]^\rho} \right\} \frac{\rho - 1}{\rho} \]  
\[ (2.2.25) \]

Similarly, by substituting equations (2.2.4), (2.2.6), (2.2.10), (2.2.12), (2.2.16), (2.2.19), (2.2.20), (2.2.21) and (2.2.22) into equation (2.2.24), the equilibrium price level in the foreign country
\[ P^* = \frac{(1 - \varepsilon)\mu}{\tau^*[1 - (1 - \varepsilon)\mu]} \left\{ \frac{\gamma[(\delta T)^a L]^\rho + (1 - \gamma)[(\delta T)^b H]^\rho}{\gamma[(\delta^* T^*)^a L^*]^\rho + (1 - \gamma)[(\delta^* T^*)^b H^*]^\rho} \right\}^{\frac{\rho}{\beta}} \quad (2.2.26) \]

To guarantee that equation (2.2.25) is equal to equation (2.2.26), this implies that \( \tau^* = \frac{\mu^2\varepsilon(1 - \varepsilon)}{1 - \mu + \varepsilon^2(1 - \varepsilon)} \).

### 2.2.4 Wage Inequality within One Country

Based on equations (2.2.19) and (2.2.20), the wage inequality in the home country, which is measured by the ratio \( \frac{w_H}{w_L} \), is equal to:

\[ \frac{w_H}{w_L} = (1 - \frac{\gamma}{\gamma})(\delta T)^{b - \alpha \rho}(\frac{H}{L})^{\rho - 1} \quad (2.2.27) \]

Similarly, according to equations (2.2.21) and (2.2.22), the wage inequality within the foreign country is:

\[ \frac{w_H^*}{w_L^*} = (1 - \frac{\gamma}{\gamma})(\delta^* T^*)^{b - \alpha \rho}(\frac{H^*}{L^*})^{\rho - 1} \quad (2.2.28) \]

### 2.2.5 International Wage Inequalities

According to equations (2.2.19), (2.2.20), (2.2.21), (2.2.22) and (2.2.25), the equilibrium wages for both skilled and unskilled workers in the two countries are:

\[ w_H = \mu \{ \gamma[(\delta T)^a L]^\rho + (1 - \gamma)[(\delta T)^b H]^\rho \}^{\frac{\rho}{\beta} - 1}(1 - \gamma)(\delta T)^{b \rho - 1} \quad (2.2.29) \]

\[ w_L = \mu \{ \gamma[(\delta T)^a L]^\rho + (1 - \gamma)[(\delta T)^b H]^\rho \}^{\frac{\rho}{\beta} - 1} \gamma(\delta T)^{b \rho - 1} \quad (2.2.30) \]

\[ w_H^* = \left\{ \frac{1}{(1 - \delta^* T^*)^{\beta\rho} + 1} \right\} \left\{ \frac{\gamma[(\delta T)^a L]^\rho + (1 - \gamma)[(\delta T)^b H]^\rho}{\gamma[(\delta^* T^*)^a L^*]^\rho + (1 - \gamma)[(\delta^* T^*)^b H^*]^\rho} \right\}^{\frac{\rho}{\beta} - 1} \quad (2.2.31) \]

\[ w_L^* = \left\{ \frac{1}{(1 - \delta^* T^*)^{\beta\rho} + 1} \right\} \left\{ \frac{\gamma[(\delta T)^a L]^\rho + (1 - \gamma)[(\delta T)^b H]^\rho}{\gamma[(\delta^* T^*)^a L^*]^\rho + (1 - \gamma)[(\delta^* T^*)^b H^*]^\rho} \right\}^{\frac{\rho}{\beta} - 1} \quad (2.2.32) \]
In addition, to guarantee the positiveness of both \(w_H^*\) and \(w_L^*\), we assume that the term 
\[1 - (1 - \varepsilon)\mu > 0\] 
or \(1 < \mu < \frac{1}{1 - \varepsilon}\). The international wage inequality for skilled labour is denoted by the ratio, \(\frac{w_H}{w_H^*}\). According to equations (2.2.29) and (2.2.31), this international wage inequality is given by:

\[
\frac{w_H}{w_H^*} = \left[\frac{1}{(1 - \delta^*)T^*} + 1\right]\left\{\frac{1 - (1 - \varepsilon)\mu}{(1 - \varepsilon)\mu}\right\}\left[\gamma(\delta^*T^*)^{\alpha - \beta\rho}(L^*)^{\rho(1 - \rho)} + (1 - \gamma)H^*\right]
\]  
(2.2.33)

and similarly, the international wage inequality for unskilled labour is represented by the ratio, \(\frac{w_L}{w_L^*}\). Based on equations (2.2.30) and (2.2.32), this international wage inequality is:

\[
\frac{w_L}{w_L^*} = \left[\frac{1}{(1 - \delta^*)T^*} + 1\right]\left\{\frac{1 - (1 - \varepsilon)\mu}{(1 - \varepsilon)\mu}\right\}\left[\gamma(\delta^*T^*)^{\alpha - \beta\rho}(L^*)^{\rho(1 - \rho)} + \gamma L^*\right]
\]  
(2.2.34)

### 2.2.6 Optimal Consumptions

According to consumption demands from the two countries and equilibrium levels of both final goods prices and wages for skilled and unskilled labour (i.e. equations (2.2.3), (2.2.4), (2.2.5), (2.2.6), (2.2.9), (2.2.10), (2.2.11), (2.2.12), (2.2.25), (2.2.29), (2.2.30), (2.2.31) and (2.2.32)), the optimal consumptions from both skilled and unskilled workers within the home country are listed as follows:

\[
C_{DH} = \varepsilon\mu\left\{\gamma[(\delta T)^\alpha L]^\rho + (1 - \gamma)[(\delta T)^\beta H^\rho]\right\}^{\frac{\rho}{2} - 1}(1 - \gamma)(\delta T)^\beta H^\rho - 1
\]  
(2.2.35)

\[
C_{DL} = \varepsilon\mu\left\{\gamma[(\delta T)^\alpha L]^\rho + (1 - \gamma)[(\delta T)^\beta H^\rho]\right\}^{\frac{\rho}{2} - 1}\gamma(\delta T)^\alpha L^\rho - 1
\]  
(2.2.36)

\[
C_{FH} = \frac{[1 - (1 - \varepsilon)\mu]\{\gamma[(\delta^*T^*)^\alpha L^*]^\rho + (1 - \gamma)[(\delta^*T^*)^\beta H^*]\}^{\frac{\rho}{2}}}{\left(\frac{1}{\gamma}\right)(\delta T)^\alpha L^\rho H^1 - \rho + H}
\]  
(2.2.37)
\[ C_{FL} = \frac{1 - (1 - \varepsilon)\mu}{1 - (1 - \varepsilon)} \left\{ \gamma[(\delta^* T^*)^\alpha L^*]^\rho + (1 - \gamma)[(\delta^* T^*)^\beta H^*]^\rho \right\}^{\frac{\rho}{\beta - \alpha}} \]

and the demands in the foreign country are:

\[ C^\ast_{DH} = \frac{1 - \mu + \varepsilon\mu^2(1 - \varepsilon)}{1 - (1 - \varepsilon)\mu} \left\{ \gamma[(\delta T)^\alpha L]^\rho + (1 - \gamma)[(\delta T)^\beta H]^\rho \right\}^{\frac{\rho}{\beta - \alpha}} \]  (2.2.38)

\[ C^\ast_{DL} = \frac{1 - \mu + \varepsilon\mu^2(1 - \varepsilon)}{1 - (1 - \varepsilon)\mu} \left\{ \gamma[(\delta^* T^*)^\alpha L^*]^\rho + (1 - \gamma)[(\delta^* T^*)^\beta H^*]^\rho \right\}^{\frac{\rho}{\beta - \alpha}} \]  (2.2.39)

\[ C^\ast_{FH} = (1 - \varepsilon)\mu \left\{ \gamma[(\delta^* T^*)^\alpha L^*]^\rho + (1 - \gamma)[(\delta^* T^*)^\beta H^*]^\rho \right\}^{\frac{\rho}{\beta - \alpha}} (1 - \gamma)[(\delta^* T^*)^\beta (H^*)^\rho - L^*] \]  (2.2.40)

\[ C^\ast_{FL} = (1 - \varepsilon)\mu \left\{ \gamma[(\delta^* T^*)^\alpha L^*]^\rho + (1 - \gamma)[(\delta^* T^*)^\beta H^*]^\rho \right\}^{\frac{\rho}{\beta - \alpha}} (1 - \gamma)[(\delta^* T^*)^\beta (L^*)^\rho - L^*] \]  (2.2.41)

The discussion regarding the above results within this subsection is included in the analysis of wage inequalities provided in section 2.4.

2.3 Simulation

This paper mainly focuses on analyzing the impact of the share of technological change (i.e. \( \delta \) and \( \delta^* \)) on both domestic and international wage inequalities (i.e. \( \frac{w_H}{w_L}, \frac{w_L^*}{w_H}, \frac{w_H}{w_L} \)). Furthermore, we also consider the impact of \( \delta \) and \( \delta^* \) on individual wages (i.e. \( w_H, w_L, w_L^* \)). The impact of \( \delta \) on \( w_H, w_H^*, w_L, w_L^* \) and \( \frac{w_L^*}{w_H} \) can be easily seen from equations (2.2.27), (2.2.29), (2.2.30), (2.2.31), (2.2.32) and (2.2.33).\(^5\) As for \( \delta^* \), it has an impact on \( w_L^* \) and \( \frac{w_L^*}{w_H} \), according to equations (2.2.28), (2.2.31), (2.2.32), (2.2.33) and (2.2.34).\(^6\) The effect of \( \delta^* \) on \( \frac{w_L^*}{w_H} \) can be easily seen from equation (2.2.28). However, the impact of \( \delta^* \) on \( \frac{w_L^*}{w_H}, \frac{w_H}{w_L^*} \) and \( \frac{w_L^*}{w_L} \) is slightly complicated, since equations (2.2.31), (2.2.32), (2.2.33) and (2.2.34) show that such impact vary depending on whether \( \alpha \) is greater or smaller than \( \beta \). In other words, the sign

\(^5\) \( \frac{w_H}{w_L} \) is not directly affected by \( \delta \) based on equation (2.2.28).

\(^6\) \( \delta^* \) has no direct impact on \( w_H, w_L \) and \( \frac{w_H}{w_L} \) based on equations (2.2.27), (2.2.29), (2.2.30).
of $\alpha - \beta$ affects whether changes in $\delta^*$ positively or negatively determines $w_H^*, w_L^*, w_H^* / w_H^*$ and $w_L^* / w_L^*$ individually. Specifically, when $\beta > \alpha$, it is difficult to see whether changes in $\delta^*$ positively or negatively affect $w_H^*$ and $w_H^* / w_H^*$ from equations (2.2.31) and (2.2.33). Similarly, when $\alpha > \beta$, it is not clear whether changes in $\delta^*$ is positively or negatively related to $w_L^*$ and $w_L^* / w_L^*$ from equations (2.2.32) and (2.2.34).  

Therefore, in order to evaluate whether changes in $\delta^*$ positively or negatively affects $w_H^*, w_L^*, w_H^* / w_H^*$ and $w_L^* / w_L^*$, we run the numerical simulation regarding the first derivatives of each $w_H^*, w_L^*, w_H^* / w_H^*$ and $w_L^* / w_L^*$ with respect to $\delta^*$ according to equations (2.2.31), (2.2.32), (2.2.33), (2.2.34), and each derivative is based on two scenarios (i.e. when $\alpha > \beta$ and when $\alpha < \beta$).

Throughout the numerical simulation, all parameter values from equations (2.2.31), (2.2.32), (2.2.33) and (2.2.34) are randomly chosen by the simulation software according to their own ranges (i.e. $\alpha, \beta, \gamma, \delta, \delta^*, \rho, \varepsilon \in (0, 1); \mu \in (1, \infty)$). Moreover, the simulation of each first derivative (i.e. first derivatives of each $w_H^*, w_L^*, w_H^* / w_H^*$ and $w_L^* / w_L^*$ with respect to $\delta^*$) has two results due to two scenarios when $\alpha > \beta$ and when $\alpha < \beta$. The two subsections below provide simulation results for all derivatives.

2.3.1 First derivatives of individual wages

As for individual wages (i.e. $w_H^*$ and $w_L^*$), “firstwh1” and “firstwh2” represent first derivatives of $w_H^*$ with respect to $\delta^*$ when $\alpha > \beta$ and when $\alpha < \beta$, respectively; “firstwl1” and “firstwl2” represent the first derivatives of $w_L^*$ with respect to $\delta^*$ when $\alpha > \beta$ and when $\alpha < \beta$, respectively.

---

7When $\alpha > \beta$, equations (2.2.31) and (2.2.33) show that an increase in $\delta^*$ would result in a decrease in $w_H^*$ but an increase in $w_H^* / w_H^*$; when $\beta > \alpha$, equations (2.2.32) and (2.2.34) reveal that an increase in $\delta^*$ would cause a decrease in $w_L^*$ but an increase in $w_L^* / w_L^*$. 

41
The simulation results show that, the first derivative of \( w^*_H \) with respect to \( \delta^* \) is positive but the first derivative of \( w^*_L \) with respect to \( \delta^* \) is negative when \( \beta > \alpha \); This implies that \( \delta^* \) is positively related to \( w^*_H \) but is negatively related to \( w^*_L \) when \( \beta > \alpha \). However, the opposite results apply when \( \beta < \alpha \), where the first derivative of \( w^*_H \) with respect to \( \delta^* \) is negative but the first derivative of \( w^*_L \) with respect to \( \delta^* \) is positive. This means that \( \delta^* \) is positively related to \( w^*_L \) but is negatively related to \( w^*_H \) when \( \beta < \alpha \).

2.3.2 First derivatives of international wage inequalities

In terms of international wage inequalities (i.e. \( \frac{w_H}{w_H^*} \) and \( \frac{w_L}{w_L^*} \)), “first1” and “first2” represent the first derivatives of \( \frac{w_H}{w_H^*} \) with respect to \( \delta^* \) when \( \alpha > \beta \) and when \( \alpha < \beta \), respectively; “first1n” and “first2n” represent the first derivatives of \( \frac{w_L}{w_L^*} \) with respect to \( \delta^* \) when \( \alpha > \beta \) and when \( \alpha < \beta \), respectively.
According to the simulation results in this subsection, the first derivative of $\frac{w_H}{w_H^*}$ with respect to $\delta^*$ is negative but the first derivative of $\frac{w_L}{w_L^*}$ with respect to $\delta^*$ is positive when $\beta > \alpha$; this implies that $\delta^*$ is positively related to $\frac{w_L}{w_L^*}$ but is negatively related to $\frac{w_H}{w_H^*}$ when $\beta > \alpha$. However, the opposite results apply when $\beta < \alpha$, where the first derivative of $\frac{w_H}{w_H^*}$ with respect to $\delta^*$ is positive but the first derivative of $\frac{w_L}{w_L^*}$ with respect to $\delta^*$ is negative. This means that
δ* is positively related to \( \frac{w_H}{w^*_H} \) but is negatively related to \( \frac{w_L}{w^*_L} \) when \( \beta < \alpha \).

2.4 Analysis of Wage Inequalities

Proposition 1 Given the total value of \( T, H, L, T^*, H^*, L^* \), \( \mu \in (1, \infty) \) and \( \varepsilon, \gamma, \rho, \alpha, \beta, \delta, \delta^* \in (0, 1) \), \( \frac{\partial (w^*_H)}{\partial \delta} > 0 \) and \( \frac{\partial (w^*_L)}{\partial \delta} < 0 \) if \( \beta > \alpha \); \( \frac{\partial (w^*_H)}{\partial \delta} < 0 \) and \( \frac{\partial (w^*_L)}{\partial \delta} > 0 \) if \( \beta < \alpha \).

Proof According to the simulation analysis in subsection 2.3.1 regarding the impact of \( \delta^* \) on both \( w^*_H \) and \( w^*_L \), the first derivative of \( w^*_H \) with respect to \( \delta^* \) is positive but the first derivative of \( w^*_L \) with respect to \( \delta^* \) is negative when \( \beta > \alpha \); This implies that \( \delta^* \) is positively related to \( w^*_H \) but negatively related to \( w^*_L \), when the productivity enhancing technological change in the foreign country has a stronger impact on improving the productivity of skilled workers compared to the unskilled. However, the opposite results apply when \( \beta < \alpha \), where the first derivative of \( w^*_H \) with respect to \( \delta^* \) is negative but the first derivative of \( w^*_L \) with respect to \( \delta^* \) is positive. This means that, when the productivity enhancing technological change in the foreign country relatively increases the productivity of unskilled workers compared with the skilled, \( \delta^* \) is positively related to \( w^*_L \) but negatively related to \( w^*_H \). In addition, the intuition of this proposition is provided in the following subsections 2.4.1 and 2.4.2.

2.4.1 The effect of productivity enhancing technological change on individual wages

Since \( \alpha \) and \( \beta \) measure the effect of productivity-enhancing technological change on \( L^* \) and \( H^* \) respectively, and the impact of such technological change is determined by whether \( \alpha \) is greater or smaller than \( \beta \) (i.e. the sign of \( \alpha - \beta \)). If \( \beta > \alpha \), this means that, in response

\[ \text{Since the price of the home-produced product is normalized to one by assumption, based on the profit-maximizing problem, the wages for both skilled and unskilled workers in the home country (i.e. } w_H \text{ and } w_L \text{) are positively related to } \delta \text{ according to equations (2.2.29) and (2.2.30).} \]
to the productivity-enhancing technological change, the productivity of skilled labour increases more than that of the unskilled. In contrast, if $\beta < \alpha$, such technological change would have a stronger impact on increasing the unskilled productivity compared with the skilled.  

With this in mind, from the consumption side, according to equations (2.2.37), (2.2.38), (2.2.41) and (2.2.42) an increase in the share of productivity enhancing technological change in the foreign country (i.e. $\delta^*$) leads to an increase in all demands for foreign-produced goods from both countries (i.e. $C_{FH}^*, C_{FL}^*, C_{FH}^* \text{ and } C_{FL}^*$). The reason is that an increase in $\delta^*$ not only causes an increase in foreign labour productivity (i.e. an increase in the productivity of skilled workers when $\beta > \alpha$ or the productivity of unskilled workers when $\alpha > \beta$), but also leads to an increase in transportation cost from foreign to home (i.e. $\tau^* - 1$), since an increase in the share of productivity enhancing technological change (i.e. $\delta^*$) leads to a decrease in the share of transportation cost reducing technological change (i.e. $1 - \delta^*$) and hence an increase in transportation cost (i.e. $\tau^* - 1$ where $\tau^* - 1 = \frac{1}{1-\delta^* T^*}$ and $T^*$ is fixed by assumption). The improvement in labour productivity reduces the price of final product in the foreign country (i.e. $P^*$), and simultaneously, the reduction in $P^*$ conquers the disadvantage of the increased transportation cost from foreign to home country (i.e. $\tau^* - 1$) and hence attracts more demands for foreign-produced goods from the home country. Such effect of $\delta^*$ on $P^*$ is shown in equation (2.2.26). As a result, lower price $P^*$ leads to higher consumption demands for foreign-produced goods from both countries, $C_{FH}^*, C_{FL}^*, C_{FH}^* \text{ and } C_{FL}^*$.

In terms of the production side, the skilled and unskilled workers are gross substitutes (i.e. $\sigma \in (1, \infty)$) in the production of final goods. When $\beta > \alpha$ in the foreign country, the productivity enhancing technological change (i.e. $\delta^* T^*$) increases the productivity of skilled labour more than that of the unskilled. Thus, given the total technological level $T^*$, an increase

---

9Due to the symmetry between two countries and for analytical simplicity, we analyze the effect of variations in $\delta^*$ in the foreign country on individual wages as well as wage inequalities, while holding $\delta$ fixed in the home country. The impact of changes in both $\delta$ and $\delta^*$ will be considered for future study.
in $\delta^*$ results in an increase in the skilled productivity compared with the unskilled. With these in mind, in order to satisfy higher demands for foreign-produced goods from both countries (i.e. $C_{FH}, C_{FL}, C_{FH}^*$ and $C_{FL}^*$), the production of final goods must increase. This requires higher demand for relatively more productive skilled labour and lower demand for relatively less productive unskilled labour in the foreign country (i.e. some unskilled workers would be replaced by the skilled), which therefore increases the skilled wage (i.e. $w_H^*$) but decreases the unskilled wage (i.e. $w_L^*$).

Conversely, if $\beta < \alpha$ in the foreign country, $\delta^*T^*$ increases the productivity of unskilled labour more than that of the skilled. Therefore, an increase in $\delta^*$ would cause the unskilled productivity to increase compared with the skilled. Given that skilled and unskilled workers are gross substitutes in the production of final goods, in order to meet higher demands for foreign-produced goods from both countries (i.e. $C_{FH}, C_{FL}, C_{FH}^*$ and $C_{FL}^*$), more production of final goods would be required, which would increase the demand for relatively more productive unskilled workers and reduce the demand for relatively less productive skilled workers in the foreign country (i.e. some skilled workers would be replaced by the unskilled). Accordingly, $w_L^*$ would increase but $w_H^*$ would decrease.

2.4.2 The effect of transportation cost reducing technological change on individual wages

If $\delta^*$ decreases, from the consumption side, according to equations (2.2.37),(2.2.38),(2.2.41) and (2.2.42), a decrease in $\delta^*$ causes a decrease in all demands for foreign-produced goods from both countries (i.e. $C_{FH}, C_{FL}, C_{FH}^*$ and $C_{FL}^*$). This is because that a decrease in $\delta^*$ not only leads to a decrease in foreign labour productivity (i.e. a decrease in skill productivity when $\beta > \alpha$ or unskilled productivity when $\alpha > \beta$), but also results in a decrease in transportation cost from foreign to home (i.e. a decrease in $\delta^*$ causes a decrease in $\tau^* - 1$, where $\tau^* - 1 = \frac{1}{(1-\delta^*)\tau^*}$). The reduction in labour productivity increases the price of final product in the foreign country (i.e.
$P^*$), although there exists a reduction in transportation cost from foreign to home country (i.e. $\tau^* - 1$) simultaneously. Such effect of $\delta^*$ on $P^*$ is shown in equation (2.2.26). As a result, higher price $P^*$ causes lower consumption demands for foreign-produced goods from both countries, $C_{FH}, C_{FL}, C^*_{FH}$ and $C^*_{FL}$.

In terms of the production side, since the skilled and unskilled workers are gross substitutes (i.e. $\sigma \in (1, \infty)$) in the production of final goods. When $\beta > \alpha$ in the foreign country, given the total technological level $T^*$, a decrease in $\delta^*$ would cause a decrease in the productivity of skilled labour more than that of the unskilled. With these in mind, low demands for foreign-produced goods from both countries (i.e. $C_{FH}, C_{FL}, C^*_{FH}$ and $C^*_{FL}$) requires less production of final goods. This leads to a decrease in the demand for less productive skilled workers compared with the unskilled in the foreign country (i.e. some skilled workers would be replaced by the unskilled). As a consequence, compared with the skilled wage (i.e. $w^*_H$), the unskilled wage (i.e. $w^*_L$) increases relatively.

Conversely, if $\beta < \alpha$ in the foreign country, a decrease in $\delta^*$ would lead to a decrease in the unskilled productivity compared with the skilled. Given that skilled and unskilled workers are gross substitutes in the production of final goods, low demands for foreign-produced goods from both countries (i.e. $C_{FH}, C_{FL}, C^*_{FH}$ and $C^*_{FL}$) require less production of final goods, which would reduce the demand for relatively less productive unskilled workers compared with the skilled in the foreign country (i.e. some unskilled workers would be replaced by the skilled). Accordingly, compared with $w^*_L$, $w^*_H$ would increase relatively.

**Proposition 2** Given the total value of $T, H, L, T^*, H^*, L^*, \mu \in (1, \infty)$ and $\varepsilon, \gamma, \rho, \alpha, \beta, \delta, \delta^* \in (0, 1)$, $\frac{\partial (w_H)}{\partial \delta} > 0$ and $\frac{\partial (w_L)}{\partial \delta^*} > 0$ if $\beta > \alpha$; $\frac{\partial (w_H)}{\partial \delta} < 0$ and $\frac{\partial (w_L)}{\partial \delta^*} < 0$ if $\beta < \alpha$;

**Proof**

$$\frac{\partial (w_H)}{\partial \delta} = (\beta \rho - \alpha \rho)(\frac{1 - \gamma}{\gamma})(\delta^\beta \alpha^\rho - 1)T^\beta \alpha^\rho \left(\frac{H}{L}\right)^{\rho - 1} > 0$$
when \( \beta > \alpha \), and

\[
\frac{\partial(w_{H}w_{L})}{\partial \delta} = (\beta \rho - \alpha \rho)(1 - \frac{\gamma}{\gamma})(\delta)^{\beta \rho - \alpha \rho - 1} T^{\beta \rho - \alpha \rho} (H/L)^{\rho - 1} < 0
\]

when \( \beta < \alpha \);

\[
\frac{\partial(w_{H}^{*}w_{L}^{*})}{\partial \delta^{*}} = (\beta \rho - \alpha \rho)(1 - \frac{\gamma}{\gamma})(\delta^{*})^{\beta \rho - \alpha \rho - 1} (T^{*})^{\beta \rho - \alpha \rho} (H^{*}/L^{*})^{\rho - 1} > 0
\]

when \( \beta > \alpha \), and

\[
\frac{\partial(w_{H}^{*}w_{L}^{*})}{\partial \delta^{*}} = (\beta \rho - \alpha \rho)(1 - \frac{\gamma}{\gamma})(\delta^{*})^{\beta \rho - \alpha \rho - 1} (T^{*})^{\beta \rho - \alpha \rho} (H^{*}/L^{*})^{\rho - 1} < 0
\]

when \( \beta < \alpha \). In addition, subsections 2.4.3 and 2.4.4 below discuss the intuition of this proposition.

2.4.3 The effect of productivity enhancing technological change on domestic wage inequality

Following the discussion in proposition 1, when \( \beta > \alpha \), the productivity-enhancing technological change increases the productivity of skilled labour more than that of the unskilled. Furthermore, since the skilled and unskilled workers are gross substitutes (i.e. \( \sigma \in (1, \infty) \)), this results in an increase in the demand for skilled labour compared with the unskilled, and hence the skilled wage increases relatively, which in turn raises the domestic wage inequality. However, when \( \beta < \alpha \), the productivity of unskilled labour increases stronger relative to the skilled, which causes a higher demand for unskilled labour and relatively increase in unskilled wage. As a result, wage inequality within one country decreases.

Specifically, from the consumption side, according to equations (2.2.37), (2.2.38), (2.2.41) and (2.2.42), an increase in \( \delta^{*} \) leads to an increase in all demands for foreign-produced goods
from both countries (i.e. $C_{FH}, C_{FL}, C^*_{FH}$ and $C^*_{FL}$). This is because an increase in $\delta^*$ not only causes an increase in foreign labour productivity (i.e. an increase in skill productivity when $\beta > \alpha$ or unskilled productivity when $\alpha > \beta$), but also leads to an increase in transportation cost from foreign to home (i.e. an increase in $\delta^*$ leads to an increase in $\tau^* - 1$, where $\tau^* - 1 = \frac{1}{(1 - \delta^*) T^*}$).

The improvement in labour productivity reduces the price of final product in the foreign country (i.e. $P^*$), and simultaneously, the reduction in $P^*$ conquers the disadvantage of increased transportation cost (i.e. $\tau^* - 1$) and hence attracts more demands for foreign-produced goods from the home country. Such effect of $\delta^*$ on $P^*$ is shown in equation (2.2.26). As a result, lower price $P^*$ leads to higher consumption demands for foreign-produced goods from both countries, $C_{FH}, C_{FL}, C^*_{FH}$ and $C^*_{FL}$.

As for the production side, when $\beta > \alpha$ in the foreign country, $\delta^* T^*$ increases the productivity of skilled labour more than that of the unskilled. Thus, given the total technological level $T^*$, an increase in $\delta^*$ results in an increase in the skilled productivity compared with the unskilled. In order to satisfy higher consumption demands for foreign-produced goods from both countries and since skilled and unskilled workers are gross substitutes (i.e. $\sigma > 1$), this would lead to a higher demand for skilled workers relative to the unskilled in the foreign country. As a result, $w^*_H$ increases but $w^*_L$ decreases, according to proposition 1. In other words, the wage inequality within the foreign country (i.e. $\frac{w^*_H}{w^*_L}$) increases.

By contrast, when $\beta < \alpha$ in the foreign country, $\delta^* T^*$ increases the productivity of unskilled labour more than that of the skilled. Therefore, an increase in $\delta^*$ would cause the unskilled productivity increases compared with the skilled. To satisfy higher demands for foreign-produced goods from both countries, there would be a higher demand for unskilled workers compared with the skilled, and hence $w^*_L$ increases but $w^*_H$ decreases, which is also shown in proposition 1. Therefore, the wage inequality within the foreign country (i.e. $\frac{w^*_H}{w^*_L}$) decreases.
2.4.4 The effect of transportation cost reducing technological change on domestic wage inequality

If $\delta^*$ decreases, from the consumption side, according to equations (2.2.37), (2.2.38), (2.2.41) and (2.2.42), a decrease in $\delta^*$ causes a decrease in all demands for foreign-produced goods from both countries (i.e. $C_{FH}, C_{FL}, C^*_{FH}$ and $C^*_{FL}$). This is because that a decrease in $\delta^*$ not only leads to a decrease in foreign labour productivity (i.e. a decrease in skill productivity when $\beta > \alpha$ or unskilled productivity when $\alpha > \beta$), but also results in a decrease in transportation cost from foreign to home (i.e. a decrease in $\delta^*$ causes a decrease in $\tau^* - 1$, where $\tau^* - 1 = \frac{1}{(1 - \delta^*)T^*}$). The reduction in labour productivity increases the price of final product in the foreign country (i.e. $P^*$), although there exists a reduction in transportation cost from foreign to home country (i.e. $\tau^* - 1$) simultaneously. Such effect of $\delta^*$ on $P^*$ is shown in equation (2.2.26). As a result, higher price $P^*$ causes lower consumption demands for foreign-produced goods from both countries, $C_{FH}, C_{FL}, C^*_{FH}$ and $C^*_{FL}$.

In terms of the production side, since the skilled and unskilled workers are gross substitutes (i.e. $\sigma \in (1, \infty)$) in the production of final goods. When $\beta > \alpha$ in the foreign country, given the total technological level $T^*$, a decrease in $\delta^*$ would cause a decrease in the productivity of skilled labour more than that of the unskilled. With these in mind, low demands for foreign-produced goods from both countries (i.e. $C_{FH}, C_{FL}, C^*_{FH}$ and $C^*_{FL}$) requires less production of final goods. This leads to a decrease in the demand for less productive skilled workers compared with the unskilled in the foreign country (i.e. some skilled workers would be replaced by the unskilled). As a consequence, compared with the skilled wage (i.e. $w^*_H$), the unskilled wage (i.e. $w^*_L$) increases relatively, according to proposition 1. In other words, the wage inequality within the foreign country (i.e. $\frac{w^*_H}{w^*_L}$) decreases.

Conversely, if $\beta < \alpha$ in the foreign country, a decrease in $\delta^*$ would lead to a decrease in
the unskilled productivity compared with the skilled. Given that skilled and unskilled workers are gross substitutes in the production of final goods, low demands for foreign-produced goods from both countries (i.e. \(C_{FH}, C_{FL}, C_{FH}^*, C_{FL}^*\)) require less production of final goods, which would reduce the demand for relatively less productive unskilled workers compared with the skilled in the foreign country (i.e. some unskilled workers would be replaced by the skilled). Accordingly, compared with \(w^*_L, w^*_H\) increases relatively based on proposition 1. Therefore, the wage inequality within the foreign country (i.e. \(\frac{w_H}{w_L}\)) increases.

In addition, since the two countries are symmetric, the discussion in subsections 2.4.3 and 2.4.4 can also be applied to the case when considering the impact of changes in \(\delta\) on wage inequality within the home country (i.e. \(\frac{w_H}{w_L}\)) while holding \(\delta^*\) fixed.

**Proposition 3** Given the total value of \(T, H, L, T^*, H^*, L^*\), \(\mu \in (1, \infty)\) and \(\varepsilon, \gamma, \rho, \alpha, \beta, \delta, \delta^* \in (0, 1)\), \(\frac{\partial (\frac{w_H}{w^*_H})}{\partial \delta^*} > 0\) and \(\frac{\partial (\frac{w_L}{w^*_L})}{\partial \delta^*} < 0\) if \(\beta < \alpha\); \(\frac{\partial (\frac{w_H}{w^*_H})}{\partial \delta^*} < 0\) and \(\frac{\partial (\frac{w_L}{w^*_L})}{\partial \delta^*} > 0\) if \(\beta > \alpha\); \(\frac{\partial (\frac{w_L}{w^*_L})}{\partial \delta} < 0\) if \(\beta > \alpha\); \(\frac{\partial (\frac{w_L}{w^*_L})}{\partial \delta} > 0\) if \(\beta < \alpha\).

**Proof** From subsection 2.3.2, the simulation analysis shows that the first derivative of \(\frac{w_H}{w^*_H}\) with respect to \(\delta^*\) is negative but the first derivative of \(\frac{w_L}{w^*_L}\) with respect to \(\delta^*\) is positive when \(\beta > \alpha\); This implies that \(\delta^*\) is positively related to \(\frac{w_L}{w^*_L}\) but is negatively related to \(\frac{w_H}{w^*_H}\), when the productivity enhancing technological change in the foreign country has a stronger impact on increasing the productivity of skilled workers compared with the unskilled. However, the opposite results apply when \(\beta < \alpha\), where the first derivative of \(\frac{w_H}{w^*_H}\) with respect to \(\delta^*\) is positive but the first derivative of \(\frac{w_L}{w^*_L}\) with respect to \(\delta^*\) is negative. This means that \(\delta^*\) is positively related to \(\frac{w_H}{w^*_H}\) but is negatively related to \(\frac{w_L}{w^*_L}\), if the productivity enhancing technological change in the foreign country relatively increases the productivity of unskilled workers compared with the skilled. In addition, the intuition of this proposition is provided in the following subsections 2.4.5 and 2.4.6.
2.4.5 The effect of productivity enhancing technological change on international wage inequality

From the consumption side, according to equations (2.2.37), (2.2.38), (2.2.41), (2.2.42), an increase in $\delta^*$ leads to an increase in all demands for foreign-produced goods from both countries (i.e. $C_{FH}, C_{FL}, C_{*FH}$ and $C_{*FL}$). This is because an increase in $\delta^*$ not only causes an increase in foreign labour productivity (i.e. an increase in skill productivity when $\beta > \alpha$ or unskilled productivity when $\alpha > \beta$), but also leads to an increase in transportation cost from foreign to home (i.e. an increase in $\delta^*$ leads to an increase in $\tau^* - 1$, where $\tau^* - 1 = \frac{1}{(1 - \delta^*)T^*}$). The improvement in labour productivity reduces the price of final product in the foreign country (i.e. $P^*$), and simultaneously, the reduction in $P^*$ conquers the disadvantage of increased transportation cost (i.e. $\tau^* - 1$) and hence attracts more demands for foreign-produced goods from the home country. Such effect of $\delta^*$ on $P^*$ is shown in equation (2.2.26). As a result, lower price $P^*$ leads to higher consumption demands for foreign-produced goods from both countries, $C_{FH}, C_{FL}, C_{*FH}$ and $C_{*FL}$.

As for the production side, when $\beta > \alpha$ in the foreign country, $\delta^*T^*$ increases the productivity of skilled labour more than that of the unskilled. Thus, given the total technological level $T^*$, an increase in $\delta^*$ results in an increase in the skilled productivity compared with the unskilled. In order to satisfy higher consumption demands for foreign-produced goods from both countries and since skilled and unskilled workers are gross substitutes (i.e. $\sigma > 1$), this would lead to a higher demand for skilled workers relative to the unskilled in the foreign country. As a result, $w_H^*$ increases but $w_L^*$ decreases, according to proposition 1. Therefore, when $\delta$ is fixed, $w_H$ and $w_L$ are unchanged based on equations (2.2.29) and (2.2.30). International wage inequality between skilled workers in different countries (i.e. $\frac{w_H^*}{w_H}$) would decrease but international wage inequality between unskilled workers in two countries (i.e. $\frac{w_L^*}{w_L}$) would
increase.

By contrast, when \( \beta < \alpha \) in the foreign country, \( \delta^*T^* \) increases the productivity of unskilled labour more than that of the skilled. Therefore, an increase in \( \delta^* \) would cause the unskilled productivity increases compared with the skilled. To satisfy higher demands for foreign-produced goods from both countries, there would be a higher demand for unskilled workers compared with the skilled, and hence \( w_L^* \) would increase but \( w_H^* \) would decrease, which is also shown in proposition 1. Therefore, while remaining \( \delta \) fixed (i.e. \( w_H^* \) and \( w_L^* \) are unchanged), \( \frac{w_L}{w_H} \) would increase but \( \frac{w_H}{w_L} \) would decrease.

2.4.6 The effect of transportation cost reducing technological change on international wage inequality

If \( \delta^* \) decreases, from the consumption side, according to equations (2.2.37), (2.2.38), (2.2.41) and (2.2.42), a decrease in \( \delta^* \) causes a decrease in all demands for foreign-produced goods from both countries (i.e. \( C_{FH}, C_{FL}, C_{FH}^* \) and \( C_{FL}^* \)). The reason is that: a decrease in \( \delta^* \) not only leads to a decrease in foreign labour productivity (i.e. a decrease in skill productivity when \( \beta > \alpha \) or unskilled productivity when \( \alpha > \beta \)), but also results in a decrease in transportation cost from foreign to home (i.e. a decrease in \( \delta^* \) leads to a decrease in \( \tau^* - 1 \), where \( \tau^* - 1 = \frac{1}{(1-\delta^*)T} \)). However, although the transportation cost \( \tau^* - 1 \) reduces, the simultaneous reduction in labour productivity increases the price of final product in the foreign country (i.e. \( P^* \)). Such effect of \( \delta^* \) on \( P^* \) is shown in equation (2.2.26). Eventually, higher price \( P^* \) would lead to a reduction in demands for foreign-produced goods from both countries, \( C_{FH}, C_{FL}, C_{FH}^* \) and \( C_{FL}^* \).

As for the production side, when \( \beta > \alpha \) in the foreign country, given the total technological level \( T^* \), a decrease in \( \delta^* \) leads to a decrease in the productivity of skilled labour more than that of the unskilled. Due to the low demands for foreign-produced goods from both countries and since skilled and unskilled workers are gross substitutes (i.e. \( \sigma > 1 \)), this would lead to
a lower demand for relatively less productive skilled workers compared with the unskilled in the foreign country. As a result, \( w_H^* \) decreases compared with \( w_L^* \), according to proposition 1. Therefore, when \( \delta \) is fixed, \( w_H \) and \( w_L \) are unchanged based on equations (2.2.29) and (2.2.30).

International wage inequality of skilled labour (i.e. \( \frac{w_H}{w_H^*} \)) would increase but international wage inequality of unskilled labour (i.e. \( \frac{w_L}{w_L^*} \)) would decrease.

By contrast, when \( \beta < \alpha \) in the foreign country, a reduction in \( \delta^* \) leads to a decrease in the productivity of unskilled labour more than that of the skilled. Therefore, facing the low demands for foreign-produced goods from both countries, there would be a lower demand for less productive unskilled workers compared with the skilled, and hence \( w_L^* \) would decrease compared with \( w_H^* \), which is also shown in proposition 1. Therefore, while remaining \( \delta \) fixed (i.e. \( w_H \) and \( w_L \) are unchanged), \( \frac{w_H}{w_H^*} \) would decrease but \( \frac{w_L}{w_L^*} \) would increase.

In addition, due to the symmetry between two countries, the argument in subsections 2.4.5 and 2.4.6 can also be applied to the case when considering the impact of changes in \( \delta \) on both \( \frac{w_H}{w_H^*} \) and \( \frac{w_L}{w_L^*} \) while remaining \( \delta^* \) fixed.

2.5 Conclusions

There have been intensive studies investigating the impact of technological change on wage inequality within one country. The skill-biased and unskill-biased technical change, and more recently, routinization-biased technical change are among the most prominent and frequently discussed trends of domestic wage inequality. Nevertheless, the impact of technological change on international wage inequality between workers with the same/similar skill level but in different countries has not been well researched. Our analysis not only fills this gap regarding the effect of technological change on international wage inequality but also provides a new theory which is able to interpret both domestic and international wage inequalities within one holistic model that has not been considered from relevant existing literature. The whole chapter has
placed the role of technological change at the centre, and according to the existing facts regarding the impact of technological change on labour productivity and international transportation cost, we introduced a new categorization of total technological change (i.e. productivity enhancing technological change and transportation cost reducing technological change), which has not been considered from previous studies. In particular, according to the effect of transportation cost reducing technological change, our analysis endogenized the reduction in international transportation cost which is caused by such technological change. This is different from existing studies regarding the effect of trade cost reduction on wage inequality, where the reduction in trade cost was assumed to be caused by an exogenous shock.

By incorporating the two types of technological change into a general equilibrium model, we considered the impact of these two types on wage inequalities both domestically and internationally. According to the analysis from our model, we have learned that wage inequality within one country, whether developed or not, is determined by its own share of productivity enhancing and transportation cost reducing technological change, and simultaneously, the impact of such technological share on domestic wage inequality varies depending on whether the impact of productivity enhancing technological change has a greater positive impact on increasing the productivity of skilled or unskilled workers. Our analysis of domestic wage inequality shows that: when technological change is mainly used for increasing labour productivity within one country, the effect of such technological change on domestic wage inequality corresponds with the existing ideas of both skill-biased and unskill-biased technical change, where technical change could increase the productivity of either skilled or unskilled workers respectively, which could increase the relevant labour demand and hence affects domestic wage inequality. Nevertheless, if technological change is mainly used for reducing international transportation cost, our analysis regarding the impact of such technological change on domestic wage inequality explains the three existing facts: the reduction in trade cost led to an increase in domestic
wage inequality across developed countries (Feenstra and Hanson, 1996, 1999, 2003). A rise in trade led to a decrease in wage inequality within developing countries, where low skilled workers are abundant (Munch and Skaksen, 2009). Moreover, some developing countries experienced the increase in domestic wage inequality (Goldberg and Pavcnik, 2007 and Burstein and Vogel, 2016).

Moreover, in an open economy consisting of one developed and one developing country, we have learned that international wage inequalities of workers with the same/similar skill level but in different countries are determined by the share of productivity enhancing and transportation cost reducing technological change in both countries, and the impact of such technological share on international wage inequalities also depends on whether productivity enhancing technological change in both countries has a greater impact on increasing the productivity of skilled or unskilled workers. In particular, our analysis regarding the impact of technological change on reducing international wage inequalities corresponds with the existing finding provided by Acemoglu, Gancia and Zilibotti (2015), where they argue that low cost of offshoring from developed to developing country could reduce international wage inequality between skilled workers (or between unskilled workers) in both countries. However, Acemoglu, Gancia and Zilibotti have only considered the cause of the reduction in international wage inequalities. Our analysis also considers the scenario regarding the effect of technological change on increasing in either international wage inequality between skill workers or between unskilled workers in different countries.
References


Katz, Lawrence., and Murphy, Kevin M., 1992, Changes in Relative Wages, 19631987: Supply and Demand Factors, Quarterly Journal of Economics, 107, 3578.


Chapter 3

Population Growth and Technological Change

3.1 Introduction

Historical evidence shows that higher population growth positively correlated with higher income during early stages of development before the Industrial Revolution. However, with more advanced economic progress in modern times, fertility rates are starting to decrease and population growth is slowing down. Also the growth rate in income per capita is continuing to rise together with human capital accumulation.

Different mechanisms were used to explain these facts in the literature with technological change being regarded as one of the most influential factors accounting for such historical evolution (e.g., Kremer 1993, Galor and Weil 2000). There are different types of technological change that are generated through different mechanisms, which may have different impacts on the growth in population, human capital and income per capita. However, existing studies treat the process of technological change as homogeneous, and various inventive processes have not been identified in existing literature.

With this in mind, this paper distinguishes two types of technological change existing in the endogenous growth theories (e.g., Romer 1986, Lucas 1988, Romer 1990): experience-based technological change and experiment-based technological change. We then incorporate these
two different changes into a simple overlapping generations framework that generates the trends regarding dynamic evolution of technological change, income per capita, population growth and human capital accumulation in the process of development and throughout human history.

A brief review of historical facts and existing literature regarding the evolution in population growth, technological change and income growth show some salient facts. We provide detailed historical facts in the appendix and only show some stylized facts which have also been nicely summarized in studies within this area (e.g., Kremer 1993, Galor and Weil 2000, Hansen and Prescott 2002): 1) Starting from the beginning of human history and followed by early development, the economy was in the Malthusian trap where both income and population were increased due to technological progress, while income per capita remained almost stationary. 2) After the Industrial Revolution, technological progress started to accelerate, human capital became more important compared with raw labour, the growth rate of income per capita increased together with the population growth rate. 3) In modern times, with further increases in the growth rate of income per capita, population growth rate slows down and even becomes negative in some countries, whilst human capital accumulation accelerates.

There have been many studies trying to explain these transitional dynamics. The Malthusian theory accounts for the evolution in both population and income per capita during early stage of development, where population size would reach the equilibrium level if there is no technological change or change in resource, such as land. An increase in either innovation or resources would only increase the level of population in the long term, while leaving the income per capita unchanged.

As development progressed, technological change broke the Malthusian trap, when income per capita continued to rise together with population. In the last century, population growth rates slowed down whilst income per capita continued to grow. One of the most widely accepted theories accounting for the negative relationship between the growth in income per
capita and population growth was introduced by Becker (1960) and Becker and Lewis (1973). They suggested that for parents, there existed a trade-off between the quality and quantity of children. As the relative return of child quality increased, quality would become more significant relative to quantity, which would eventually lead to the substitution of quality for quantity. In addition, Becker and Lewis argued that the adequately high income elasticity of quality resulted in a reduction in quantity but an increase in income level, and this accounted for the negative relationship between population growth and income. Barro and Becker (1989) took the interaction between quality and quantity into consideration when analyzing changes in fertility. They also considered that due to a higher degree of altruism between parents and children, there was a higher steady state rate of population growth, which negatively affected the growth rate in income per capita.

Based on these studies, Becker, Murphy and Tamura (1990), Lucas (2002), Jones (2001), Becker, Glaeser and Murphy (1999), Galor and Weil (1999, 2000), Fernandez-Villaverde (2001), Galor and Moav (2002), Hansen and Prescott (2002), and Hazan and Berdugo (2002) analyzed changes in both income and population growth throughout human history. In particular, they argued that the increase in returns to human capital generated further economic growth. Motivated by this increasing return, parents would focus on quality more than quantity. This accounted for the interaction between demographic transition and economic growth in more recent times.

Galor and Weil (1996) emphasized that the increase in relative wages for women in developed countries had a negative impact on fertility due to the increase in the opportunity cost of child-rearing. Nevertheless, output growth was stimulated because of the increasing level in labour force participation. Lord and Rangazas (2006) argued that, within the US, industrialization was the main cause of the reduction in fertility during the nineteenth century. During this period there existed a decrease in income from family production, which reduced
the demand for children. In the twentieth century, the increase in schooling for older children mainly accounted for the reduction in fertility in the US.

Some other studies argued that either rising longevity or higher old age survival probability was also a source of the transition, which affected the replacement of quantity with quality and hence the demographic change. Long term increasing longevity positively affected both the level of human capital and growth rate of income per capita, whereas the opposite applied when considering the relationship between increasing longevity and reducing fertility (Zhang and Zhang, 2001). Similarly, Hashimoto and Tabata (2013) analyzed the effect of higher old age survival probability on fertility and education, which also influenced the investment in research and development and output per capita in the long term.

Existing studies in this area highlighted the importance of technological change in interpreting the historical evolution in both population and income growth. However, technological change was analyzed from the aggregated level and existing theoretical frameworks were silent on ways that technological change was generated. When considering endogenous growth theories, there are two different types of technological change that can be identified, although they have not previously been well categorized within this field. Different types of technological change may have different impacts on population growth, human capital accumulation and the growth in income per capita, which accordingly may have differing effects on transitional dynamics. Motivated by this, our research firstly contributes to the existing literature in the field of endogenous growth theory by distinguishing two types of technological change, both of which are based on different aspects of technological invention. Below we provide specific discussion regarding two types of technological change and consider their roles in the context of both pre-modern and modern times.

Although the ideas of two different technological changes have been widely adopted among existing endogenous growth studies, the distinction between the two types have not been made
clear in this field. Two types of technological change can be identified: those generated through learning by doing and those created through intentional investment. Technological change from learning by doing is based on the experiences gained from the production process and is mostly unintentional (e.g., Arrow 1962, Sheshinski 1967, Romer 1986, Barro and Sala-i-Martin 1995). Technological change invented through intentional investment relies on purposeful experiments (e.g., Barron 1988, Romer 1990, Galor and Tsiddon 1997). We call the first type, experience-based technological change and the second type, experiment-based technological change. This follows Lin (1995) in his study of the Chinese civilization, who also distinguished experience-based technological change and experiment-based technological change.

The experience-based technological change is mainly based on past experiences gained from, for example, production or investment, which is mostly unintentional. This type of technology is mostly free of charge and hence no requirement is needed for both economic considerations and property rights. The process of learning by doing considers the positive relationship between experience and productivity. The newly invented technology or knowledge was a by-product from investment and/or production. For instance, while increasing the physical capital, firms also learn how to improve the efficiency of production. In other words, there exists a simultaneous increase in both capital stock and stock of knowledge (e.g., Arrow 1962, Sheshinski 1967, Romer 1986, Barro and Sala-i-Martin 1995). Some empirical studies also support the idea that higher experience is matched by higher productivity. For instance, shipbuilding and airframe manufacturing (e.g., Wright 1936, Searle 1946, Asher 1956, Rapping 1965, Schmookler 1966).

The experiment-based technological change requires investment in both physical and human capital and is normally intentional. This type of invention is normally related to many experiments carried out in research departments, which involves problem-solving research relating to trial and error (Barron, 1988), and the idea of such invention is correspondent with
empirical studies from Marples (1961) and Allen (1966). In order to reward the investment that went into the invention, it requires economic considerations and property right protection. Many endogenous growth studies incorporated the idea of experiment-based technological change into the set-up of technological invention. For example, Romer (1990) and Galor and Tsiddon (1997) considered the role of human capital in producing new technology.

Population size has a huge impact on the growth rate of experience-based technological change. With a higher population, there is a higher level of production, which in turn creates more experience and hence more innovation. However, the experiment-based technological change is not affected by the level of population. This type of technology is created by inventors with specific purposes. Therefore, where artisans may learn one technique within a set period, inventors may do more than one trial in the same period. Extrapolating this, during a certain period, the amount of experiments operated by inventors may be equivalent to the total amount of production from, for example, artisans during their lifetimes. These key characteristics for both technological changes have been considered in other literature.

Kremer (1993) regarded variations in population level as the measurement of innovation, where technological change was positively affected by the level of population, which is consistent with the feature of experience-based technological change. The theoretical model in Romer (1990) highlighted the characteristics of experiment-based technological change, where new technology was generated by human capital within the research sector. Moreover, with regard to the predominance of technological change across different periods, Lin (1995) showed that the style of innovation was different from pre-modern to modern periods. The use of experience-based technology in the pre-modern period was widely accepted, whereas the experiment-based technology started to play a major role after the scientific revolution during the seventeenth century.

According to the characteristics of both technological changes, we assume that the cre-
ation of experience-based technology is positively related to population level, and the invention of experiment-based technology is regarded as human capital intensive. Our research also takes into account the proven fact regarding the predominance between two types of technological change from pre-modern to modern periods. With this in mind, our research places the role of two types of technological change at the centre when explaining the evolution in population growth, human capital accumulation and growth in income per capita from pre-modern to modern times. Existing study investigated by Galor and Weil (2000) considered the impact of technological change on such evolution, however, they neglected various types of technological change and only considered the impact of total technological change on such evolution. Motivated by this, according to our categorization of technological change (i.e. experience-based and experiment-based technological changes) based on endogenous growth theory, our research digs into this deeper and shows that these two types of technological change have various impacts on the evolution in population growth, growth in human capital and growth in income per capita, which provides a complementary theory to Galor and Weil (2000). This is our second contribution. Mathematically, we incorporate these two types of technological change into a unified overlapping generations framework that generates dynamics in population growth, growth in human capital and growth in wage income per capita from prehistoric times to the present day. Our results reveal that gradual transition from experience-based to experiment-based technological change (i.e. the gradual decrease in growth rate of experience-based technological change and gradual increase in growth rate of experiment-based technological change over time) plays a fundamental role in determining population growth, growth in human capital and growth in wage income per capita, which are generally consistent with relevant stylized facts.

The remainder of this chapter is organized as follows. Section 3.2 develops the model; Section 3.3 discusses the dynamics of the model and studies the propositions; Section 4 concludes, and the last section provides appendix.
3.2 The Model

The set-up of our model considers the overlapping generations economy. The economy is formed by both households and firms. Each generation, \( t \), where \( t \in [1, \infty) \), consists of \( L_t \) identical individuals and each of them lives for two periods encompassing childhood at period \( t - 1 \) and adulthood at period \( t \). During childhood, each child consumes a portion of their own parent’s time, there is no labour force participation and consumption in this period. In adulthood, each parent is endowed with one unit of time and they allocate this among labour force participation, consumption and child-rearing. In child-rearing, there is a trade-off between quantity and quality of children for each parent, where quantity denotes the number of children a parent has. Each identical individual is endowed with identical level of raw labour meaning that the population level is the level of raw labour. Each raw labour can be augmented to human capital by investment in education from parents. For simplicity, the education level (i.e. the quality of children) for each child is assumed to be identical. Under this set-up, every individual in this economy has identical levels of raw labour, and a given level of human capital, which is determined by the amount of the investment in education.

There are two types of technology in this economy: experiment-based technology, \( T \) and experience-based technology, \( A \). Whilst the experiment-based technology is produced purposefully by the research sector, the experience-based technology is a by-product of final goods production.\(^1\) As discussed earlier, we assume that the generation of experience-based technology depends on the number of people in the economy. Logically, such an idea follows the argument from Kremer (1993), where a higher population level increases the number of potential inventors who stimulate technological progress. Thus, the generation of experience-based technology is positively related to population level. By contrast, the idea of experiment-based technology does not require a specific sector.

\(^1\)Due to our assumption of inventing experience-based technology, the production of such technology does not require a specific sector.
technology is based on Romer (1990), where human capital positively affects technological progress. We assume that both types of technology not only increase the productivity but also provide various designs for the production in intermediate goods sectors.

There are five sectors in this economy: the research sector, the traditional intermediate goods sector, the modern intermediate goods sector, the traditional final goods sector and the modern final goods sector. In the research sector, firms are perfectly competitive, and they use human capital and the existing stock of knowledge to produce the experiment-based technology, which provides the design for the production in the modern intermediate goods sector. Firms in both traditional and modern intermediate goods sectors are monopolistically competitive. Each firm is a monopoly and produces one type of intermediate good and sets the price of the intermediate good it produces. Each unit of traditional (modern) intermediate good is produced by renting one unit of forgone traditional (modern) final output. The differentiated intermediate goods produced in the traditional intermediate goods sector and modern intermediate goods sector are used for the production in the traditional final goods sector and modern final goods sector, respectively. In addition, firms in both final goods sectors are perfectly competitive and they produce homogenous products. The production in the traditional final goods sector uses raw labour and traditional intermediate goods. The modern final goods sector combines both human capital and modern intermediate goods to produce final output. Moreover, it is worth emphasizing that, due to the assumption that each individual is classed as not only raw labour but also human capital, they allocate their ability of human capital to both the research sector and the modern final goods sector, and contribute to the traditional final goods sector by using the ability of raw labour.

In addition, our model is not an extension of any existing framework. However, in terms

---

2We simply name the intermediate goods, which are produced in traditional and modern intermediate goods sectors, as traditional and modern intermediate goods, respectively. This also applies to the concepts of traditional and modern final goods.
of technological change and its impact on population growth and income level, this is related to the relevant area in Galor and Weil (2000), where technological progress was analyzed from the aggregate level determined by both education level and population size. This overall progress affected the growth in both population and income. In our model, we categorize the overall technological progress by distinguishing two types of technological change, each of which is determined by either education level or population size. Accordingly, our model analyzes the effect of each technological change on the growth in both population and income, which provides a complementary theory to Galor and Weil (2000).

3.2.1 Households

At period \( t \), parents obtain their utilities from consumption, number of children, and human capital for each child. The utility function for each parent is represented by a logarithmic utility function, which is separable. This has been widely used in existing literature regarding the interaction of economic growth in the long run with heterogeneity in terms of income level and child-rearing choices (e.g., Galor and Moav 2002, de la Croix and Doepke 2003, Moav 2005, Vogl 2016).

\[ u_t(c_t, n_t, h_{t+1}) = (1 - \delta)logc_t + \delta[logn_t + \lambda log(w_{h_{t+1}, h_{t+1}})] \] (3.2.1)

where \( c_t \) denotes the consumption by each single parent, \( n_t \) is the quantity of children per parent, \( h_{t+1} \) represents human capital per child, \( w_{h_{t+1}} \) is the unit wage for each unit of human capital, and \( w_{h_{t+1}, h_{t+1}} \) is the wage for each human capital. \(^3\)The parameter \( \delta \), where \( \delta \in (0, 1) \), is

\(^3\)Parents care about the number of children as well as the education level for each child. Higher wage payment for human capital would motivate parents to invest more in education for each child rather than having more children. This plays a crucial role in affecting the trade-off between children’s quantity and quality. Therefore, we use \( w_{h_{t+1}, h_{t+1}} \) rather than \( h_{t+1} \) to reflect this trade-off. In other words, the preference of each parent comes from consumption, the number of children and their potential future wage income for human capital.
the weight that each single parent spends on child-rearing both in quantity and quality relative to consumption. The parameter $\lambda$, where $\lambda \in (0, 1)$, emphasizes the importance of quality compared with quantity.

The growth rate of human capital per child is assumed to be positively determined by their education level. Moreover, based on our assumption in terms of the characteristics for both experience-based and experiment-based technologies, higher creation in experiment-based technology requires more inventors (i.e. human capital). By contrast, the increase in the amount of raw labour (i.e. population level) raises the level of experience-based technology. In other words, the experiment-based technology is human capital augmenting and hence higher growth rate of such technology results in higher growth rate of human capital, whereas the growth rate of human capital is negatively related to the growth rate of experience-based technology, which is raw labour augmenting. The evolution of human capital $h$ from period $t$ to period $t + 1$ is given as below:

$$h_{t+1} = \eta h_t e_{t+1} \left( \frac{g^T_{t+1}}{g^A_{t+1}} \right) + h_t$$  \hspace{1cm} (3.2.2)

where $\eta > 0$ and $\sigma \in (0, 1)$. $e$ denotes the education level per child, $g^T_{t+1}$ and $g^A_{t+1}$ represent the growth rates of experiment-based technology and experience-based technology from period $t$ to period $t + 1$, respectively (i.e. $g^T_{t+1} = \frac{T_{t+1} - T_t}{T_t}$ and $g^A_{t+1} = \frac{A_{t+1} - A_t}{A_t}$, where $T$ and $A$ represent the level of experiment-based technology and the level of experience-based technology, respectively).

Equation (3.2.2) shows that the growth rate of human capital per child, $\frac{h_{t+1} - h_t}{h_t}$, is positively correlated with changes in both $e_{t+1}$ and $g^T_{t+1}$. Nevertheless, the negative relationship applies when considering the effect of variations in $g^A_{t+1}$ on $\frac{h_{t+1} - h_t}{h_t}$. 4

Due to the assumption that the production of experience-based technological change is raw labour-augmenting and the production for experiment-based technological change is human capital-augmenting, an increase in the production of experience-based technological change would require more demand for raw labour compared with human capital. This would motivate parents to have more children rather than invest-
Households generate income from providing their raw labour and human capital. They allocate their income between consumption and child rearing both in quantity and quality. The budget constraint of an individual is given by,

\[ c_t + (w_h h_t + w_L L_t)n_t(\tau + e_{t+1}) \leq w_h h_t + w_L L_t \]  

(3.2.3)

where \( c_t \) is the consumption at time \( t \), \( w_h h_t + w_L L_t \) represents the income per capita received from providing human capital and raw labour. \( \tau \), where \( \tau \in (0, 1) \), denotes the fixed time cost which is needed to rear a child (i.e. to produce raw labour). We normalize the time allocation for each unit of education to one. \( \tau + e_{t+1} \) represents the time spent raising one child with education level \( e_{t+1} \). Thus, the total rearing expenditure for each child with education level \( e_{t+1} \) is represented by \( (w_h h_t + w_L L_t)(\tau + e_{t+1}) \).5

Each parent chooses the amount of consumption, number of children and their education level, based on the budget constraint and the production of human capital. This optimization problem provides the following results:

\[ n_t = \frac{\eta \delta (1 - \lambda)}{\tau \eta - \left( \frac{g_{t+1}}{g_{t+1}} \right)^{\sigma}} \]  

(3.2.4)

5 Our budget constraint is similar to the one in Galor and Weil (2000), where they also considered that the income for each parent was divided between consumption and child-rearing both in quantity and quality. Their budget constraint was given by \( c_t + w_t h_t n_t (\tau^q + \tau^e e_{t+1}) \leq w_t h_t \), where \( w_t h_t \) denoted the income for each parent, \( \tau^q + \tau^e e_{t+1} \) was the time spent on one child with education level \( e_{t+1} \). \( w_t h_t (\tau^q + \tau^e e_{t+1}) \) represented the cost of rearing a child with education level \( e_{t+1} \), and \( c_t \) denoted the consumption.
\[ e_{t+1} = \frac{\lambda \eta \tau - (\frac{g_{t+1}^T}{g_{t+1}^A})^\sigma}{\eta(1 - \lambda)} \]  

(3.2.5)

By substituting equation (3.2.5) into equation (3.2.2), human capital for each child can be written as:

\[ h_{t+1} = \left[ \left( \frac{g_{t+1}^T}{g_{t+1}^A} \right)^\sigma (\eta \lambda \tau) - \lambda \right] \frac{h_t}{1 - \lambda} \]  

(3.2.6)

From equations (3.2.4) and (3.2.6), the total supply of human capital in this economy is:

\[ H_{t+1} = L_t h_{t+1} = \left( \frac{g_{t+1}^T}{g_{t+1}^A} \right)^\sigma (\lambda \delta L_t h_t) \]  

(3.2.7)

and from equations (3.2.3), (3.2.4) and (3.2.5), the optimal consumption level is:

\[ c_t = (w_h h_t + w_L L_t)(1 - \delta) \]  

(3.2.8)

3.2.2 Firms

The research sector

Firms in this sector participate perfect competition and they produce various types of experiment-based technology which provide designs for the production in the modern intermediate goods sector. According to the assumption from Romer (1990), newly invented technology is positively determined by both human capital and stock of knowledge. This is similar to the characteristic of experiment-based technology, where inventors are required to produce such technology according to the specific target of innovation. We regard inventors as human capital and by adopting Romer’s idea, the production function in this sector is given by:

\[ \Delta T_{t+1} = \phi T_t^A H_{T,t} \]  

(3.2.9)
where $\phi$ is a positive parameter. Equation (3.2.9) simply reveals that, from period $t$ to period $t+1$, competitive firms in this sector use stock of knowledge in experiment-based technology, $T_t$, and human capital, $H_{T,t}$, to create the amount of new experiment-based technology, $\Delta T_{t+1}$ (i.e. $T_{t+1} - T_t$). In addition, $\Lambda \in (0,1)$ implies that the production of new experiment-based technology exhibits increasing returns to scale, which allows that past inventions (i.e. stock of knowledge) may increase the research productivity in the present (i.e. the “standing-on-shoulders” effect) (Jones, 1999).

The profit function in the research sector is $P_{T,t}T^\Lambda - w_{H_{T,t}}H_{T,t}$, where $P_{T,t}$ is the price of each newly invented research product and $w_{H_{T,t}}$ represents the wage for human capital in this sector. Since perfect competition prevails in this sector, the profit-maximization condition leads to the following result:

$$w_{H_{T,t}} = P_{T,t}T^\Lambda$$

The production of experience-based technology

The invention of experience-based technology, which provides the design for the production in the traditional intermediate goods sector, only depends on the experience gained during the final goods production. In other words, no specific sector is required for generating such innovation. This feature is reflected in the assumption from Kremer (1993), where the newly invented technology is positively and nonlinearly related to population level and existing level of technology. Therefore, in our framework, we adopt this nonlinear relationship from Kremer.

---

6 The production function in the research sector could be in a more general form by adding the duplication effect (i.e. $\Delta T_{t+1} = \phi T^\Lambda H^\Psi_{T,t}$, where $\Psi \in (0,1)$). Jones (1995, 1999) considered such effect as the stepping on toes effect, which meant that too many people were involved in research production causing duplication of activities leading to a decrease in efficiency regarding the use of resources. (i.e. the parameter $\Psi$ implies diminishing returns to increasing the number of human capital, which reflects the duplication in idea discovery). However, for analytical simplicity, we ignore this duplication effect.

7 In Kremer (1993), the general formulation was given by the equation, $\dot{A} = gp^\Psi A^\phi$, where $\Psi, \phi \in (0,1)$, $\dot{A}$ represented the amount of newly invented technology, $A$ denoted the existing level of technology, $p$ denoted
to describe the discovery of experience-based technology. The production function is given as below:

\[ \Delta A_{t+1} = \mu A_t^\gamma L_t^\theta \]  

(3.2.11)

where \( \mu \) is a positive parameter. \( A \) denotes the stock of knowledge, \( \Delta A_{t+1} = A_{t+1} - A_t \) represents the amount of new technology being discovered from period \( t \) to \( t + 1 \). \( L \) represents the population level, which can also be regarded as the level of raw labour. In addition, \( \gamma, \theta \in (0, 1) \) allows for decreasing returns to scale in the discovery of new experience-based technology, where \( \theta \) reflects the diminishing returns to increasing the level of population (i.e. duplication in idea discovery), and \( \gamma \) implies that the productivity of discovering new technology is an increasing function of the stock of knowledge that has been created in the past.

The traditional final goods sector

Firms are perfectly competitive in this sector. They use raw labour and traditional intermediate goods to produce final output. The production function in this sector is assumed to be homogeneous of degree one (i.e. constant returns to scale), which implies that output in this sector can be represented by the production of a single firm (Romer, 1990). The production function in this sector at period \( t \) is given by:

\[ Y_{1t} = L_t^{1-\beta} \sum_{j=1}^{A_t} x_{j,t}^{\beta} \]  

(3.2.12)

where parameter \( \beta \in (0, 1) \), \( Y_1 \) represents the final output produced in the traditional final goods sector, \( A \) is the level of experience-based technology, which determines the number of types of traditional intermediate goods. \( x_j \) denotes the amount of a certain type of traditional 

the population level and \( g \) was the research productivity for each person.
intermediate good $j$, where $j = 1, \ldots, A$, used in traditional final goods production. As discussed earlier, all raw labour or population, $L$, in this economy, participate in the production of the traditional final goods.

We normalize the price of traditional final output to one, and the profit function of this sector in period $t$ is given by $L_t^{1-\beta} \sum_{j=1}^{A_t} x_{j,t}^\beta - w_{L,t} L_t - \sum_{j=1}^{A_t} p_{j,t} x_{j,t}$, where $w_{L,t}$ represents the wage payment for raw labour and $p_{j,t}$ denotes the price of each type of traditional intermediate good $j$. The profit-maximization condition leads to the following results:

$$w_{L,t} = (1 - \beta)L_t^{-\beta} \sum_{j=1}^{A_t} x_{j,t}^\beta = (1 - \beta) \frac{Y_{1,t}}{L_t} \quad (3.2.13)$$

$$p_{j,t} = \beta L_t^{1-\beta} x_{j,t}^{\beta-1} \quad (3.2.14)$$

The modern final goods sector

Perfect competition prevails in this sector. Competitive firms employ human capital and purchase the intermediate goods from the modern intermediate goods sector in order to produce the final output. Similar to the structure of the production function in the traditional final goods sector, such a function in the modern final goods sector is in Cobb-Douglas form with constant returns to scale. The production function in this sector at period $t$ is given by:

$$Y_{2,t} = H^{1-\alpha}_{Y,t} \sum_{i=1}^{T_t} x_{i,t}^{\alpha} \quad (3.2.15)$$

where parameter $\alpha \in (0, 1)$. $Y_2$ is the final output produced from the modern final goods sector. $H_Y$ represents human capital employed in this sector. $T_t$ denotes the amount of experiment-based technology, which determines the number of differentiated modern intermediate goods. $x_i$ denotes the amount of intermediate goods with type $i$ used in final goods production, where
i = 1, ..., T.

Competitive firms maximize profits while facing the costs coming from both wage payment for human capital, \( w_{HY,t} \), and prices \( p_{i,t} \) for intermediate goods, where \( i = 1, ..., T \). By normalizing the price of final product in the modern final goods sector to one, the profit of this sector in period \( t \) is \( \sum_{i=1}^{T} x_{i,t}^\alpha - w_{HY,t} H_{Y,t} - \sum_{i=1}^{T} p_{i,t} x_{i,t} \). Maximizing such profit provides the indirect demand functions below:

\[
\begin{align*}
    w_{HY,t} &= (1 - \alpha) H_{Y,t}^\alpha \sum_{i=1}^{T} x_{i,t}^\alpha = (1 - \alpha) \frac{Y_{2t}}{H_{Y,t}} \quad (3.2.16) \\
    p_{i,t} &= \alpha H_{Y,t}^{1-\alpha} x_{i,t}^{\alpha-1} \quad (3.2.17)
\end{align*}
\]

The traditional intermediate goods sector

Under monopolistic competition, firms produce differentiated traditional intermediate goods with various types. Each type of traditional intermediate good \( j \), where \( j = 1, ..., A \), is produced by a single firm that holds the design/blueprint of intermediate good \( j \). The ownership of the design for producing intermediate good \( j \) is protected by perfect patent protection. The production of one unit of each type costs one unit of forgone final output produced in the traditional final goods sector. Each firm decides the optimal price level of its own product. At each period \( t \), the profit for the firm that produces the intermediate good of type \( j \) is given by \( (p_{j,t} - 1)x_{j,t} \), where 1 is the marginal cost of production, \( x_j \) denotes the quantity of intermediate good of type \( j \) produced, and \( p_j \) represents its price.

Each monopoly maximizes profit according to the demand for traditional intermediate goods from the traditional final goods sector. By substituting equation (3.2.14) (i.e. the inverse demand for each type of intermediate product from the traditional final goods sector) into the profit function in the traditional intermediate goods sector \( (p_{j,t} - 1)x_{j,t} \), the profit-maximization
condition gives $x_{j,t} = \beta \frac{2}{1-\eta} L_t$, where $j = 1, \ldots, A$. Furthermore, by substituting this result into equation (3.2.14), the price of traditional intermediate good $j$ at period $t$ is $p_{j,t} = \frac{1}{\beta}$, where $j = 1, \ldots, A$. Since all types of intermediate goods are produced in the same quantity with the same price at each period, the index denoting the type for intermediate goods (i.e. index $j$) can be omitted. Therefore, the associated profit-maximization problem in this sector leads to the following results:  

$$x_{j,t} = x_{1t} = \beta \frac{2}{1-\eta} L_t$$  (3.2.18) 

$$p_{j,t} = p_{1t} = \frac{1}{\beta}$$  (3.2.19)

The modern intermediate goods sector

Monopolistic competition prevails in the modern intermediate goods sector. Each type of modern intermediate good $i$ is produced by a single firm $i$, where $i = 1, \ldots, T$. In other words, each firm is a monopoly and hence sets the price of the modern intermediate good it produces. Each firm has the ownership of a certain design for producing a certain type of modern intermediate good, which is well protected by perfect patent protection. In addition, one unit of each type of modern intermediate good is produced by renting one unit of forgone final output produced in the modern final goods sector. Accordingly, the profit function for a firm which produces the $i$th modern intermediate good at each period $t$ can be represented by $(p_{i,t} - 1)x_{i,t}$, where $1$ is the marginal cost of production, $x_i$ denotes the quantity of $i$th modern intermediate good produced, and $p_i$ represents its price.

Facing the demand for each type of modern intermediate goods from the modern final goods sector at each period $t$ (i.e. equation (3.2.17)), each monopoly maximizes its profit $(p_{i,t} - 1)x_{i,t}$, where $i = 1, \ldots, T$. Such profit-maximization problem leads to the result: $x_{i,t} =$

---

8We use $x_{1t}$ and $p_{1t}$ to denote the level of quantity and price, respectively. The idea is to differentiate from such level in the modern intermediate goods sector, which are represented by $x_{2t}$ and $p_{2t}$.
\[ \alpha \frac{2}{\alpha} H_{Y,t}, \text{ where } i = 1, \ldots, T. \] Furthermore, by substituting this result into equation (3.2.17), the price for each type of modern intermediate good \( i \) at period \( t \) is given by \[ p_{i,t} = \frac{1}{\alpha}, \] where \( i = 1, \ldots, T. \) Since, at each period, all types of modern intermediate goods are produced in the same quantity and the price for each type is the same, we neglect the index \( i \) denoting the type for modern intermediate goods for convenience. Therefore, the profit-maximization conditions in this sector are given by:

\begin{align*}
    x_{i,t} &= x_{2t} = \alpha \frac{2}{\alpha} H_{Y,t} \\
    p_{i,t} &= p_{2t} = \frac{1}{\alpha}
\end{align*}

(3.2.20)

(3.2.21)

By substituting equations (3.2.20) and (3.2.21) into the profit function at each period \( t, (p_{i,t} - 1)x_{i,t}, \) the profit from selling each type of modern intermediate good \( i, \) where \( i = 1, \ldots, T, \) is:

\[ \pi_{i,t} = \pi_{2t} = (1 - \alpha)\alpha \frac{1+\alpha}{\alpha} H_{Y,t} \]

(3.2.22)

We assume the free entry into the production of modern intermediate goods, which means that in equilibrium the profit from selling each type of modern intermediate good equals the cost of purchasing a design from the research sector. Moreover, we assume that each monopoly in the modern intermediate goods sector holds a design with patent for one period (i.e. one generation). For the following period, the monopoly right of producing a certain type of modern intermediate good is passed on to the next generation. Under these two assumptions, we neglect intertemporal problems of design holding and design pricing. Therefore, free entry indicates that \( \pi_{2t} = P_T, t \) where \( P_T \) denotes the price of each newly invented research product from the research sector which provides the design for the production in the modern intermediate goods sector.
3.2.3 Market equilibrium

In equilibrium, the wage for human capital in the research sector equals such wage in the modern final goods sector, and according to equations (3.2.10) and (3.2.16), we derive:

\[ P_{T,t} \phi^A_T = (1 - \alpha) \frac{Y_{2t}}{H_{Y,t}} \quad (3.2.23) \]

The condition of free entry in the modern intermediate goods sector together with equation (3.2.22) imply:

\[ P_{T,t} = \pi_{2t} = (1 - \alpha) \alpha^{-\frac{1-\alpha}{\alpha}} \frac{H_{Y,t}}{H_{Y,t}} \quad (3.2.24) \]

By using equations (3.2.23) and (3.2.24) to remove \( P_{T,t} \), the demand for human capital in the modern final goods sector \( H_{Y,t} \) is given by:

\[ H_{Y,t} = \frac{T_t^{1-A}}{\phi \alpha} \quad (3.2.25) \]

Since in equilibrium total supply of human capital equals total demand from both research and modern final goods sectors (i.e. \( H_{T,t} + H_{Y,t} = H_t \)) and together with \( H_{Y,t} \) from equation (3.2.25), the result of \( H_{T,t} \) is:

\[ H_{T,t} = H_t - \frac{T_t^{1-A}}{\phi \alpha} \quad (3.2.26) \]

By substituting \( H_{T,t} \) (i.e. equation (3.2.26)) into the production function in the research sector (i.e. equation (3.2.9)), the evolution of experiment-based technology \( T \) is:

\[ T_{t+1} = \phi T_t^A H_t - \frac{1 - \alpha}{\alpha} T_t \quad (3.2.27) \]
and the evolution of experience-based technology is simply revealed by equation (3.2.11):

\[ A_{t+1} = \mu A_t L_t^\theta + A_t \]  

(3.2.28)

To derive the equilibrium wage for human capital at each period \( t \), by substituting equations (3.2.24) and (3.2.25) into equation (3.2.10), the result of \( w_{H_t} \) is given by:

\[ w_{H_t} = (1 - \alpha)\alpha \frac{2\theta}{2-\alpha} T_t \]  

(3.2.29)

and the equilibrium wage for raw labour at each period \( t \), \( w_{L_t} \), is obtained by substituting equation (3.2.18) into equation (3.2.13), which gives:

\[ w_{L_t} = (1 - \beta)\beta \frac{2\eta}{2-\beta} A_t \]  

(3.2.30)

3.3 Dynamics of Human Capital, Population, Technology and per capita Wage Incomes

3.3.1 Dynamics of human capital and population

According to equation (3.2.7), dynamic change in the level of human capital from period \( t \) to period \( t + 1 \) is captured as below:

\[ \frac{H_{t+1}}{H_t} = \left( \frac{g_{t+1}^T}{g_{t+1}^A} \right)^\sigma (\lambda \eta \delta) \]  

(3.3.1)

The population size at period \( t + 1 \), \( L_{t+1} \), is represented by the equation \( L_{t+1} = L_t n_t \), where \( L_t \) denotes the population level at period \( t \), and \( n_t \) is the quantity of children per parent and hence \( n_t - 1 \) is the population growth rate. According to the result of \( n_t \) (i.e. equation (3.2.4)),

81
the dynamic change in population level is given by:

\[
\frac{L_{t+1}}{L_t} = \frac{\eta \delta (1 - \lambda)}{\tau \eta - \left(\frac{g_{A_t}}{g_{T_t}}\right)^\sigma}
\]  

(3.3.2)

Equations (3.3.31) and (3.3.32) reveal that, from period \( t \) to \( t + 1 \), where \( t \in [1, \infty) \), the extent of changes in growth rates for both human capital and population are affected by the ratio of growth rate in experiment-based technology to growth rate in experience-based technology (i.e. \( \frac{g_{T_t}}{g_{A_t}} \)). Given that \( \sigma, \delta, \lambda, \tau \in (0, 1) \) and \( \eta > 0 \), based on equation (3.3.31), the first and second derivatives with respect to \( \frac{g_{T_t}}{g_{A_t}} \) provide that:

\[
\frac{d}{d\left(\frac{g_{T_t}}{g_{A_t}}\right)} \left( \frac{H_{t+1}}{H_t} \right) = \sigma \left(\frac{g_{T_t}}{g_{A_t}}\right)^{\sigma-2} \frac{\lambda \eta \delta}{1 - \lambda} > 0
\]

and

\[
\frac{d^2}{d\left(\frac{g_{T_t}}{g_{A_t}}\right)^2} \left( \frac{H_{t+1}}{H_t} \right) = 2 \eta \delta (1 - \lambda) \tau \eta - \left(\frac{g_{T_t}}{g_{A_t}}\right)^{-3} \sigma^2 \left(\frac{g_{T_t}}{g_{A_t}}\right)^{-2} > 0
\]

From equation (3.3.32), two derivatives are given by:

\[
\frac{d}{d\left(\frac{g_{T_t}}{g_{A_t}}\right)} \left( \frac{L_{t+1}}{L_t} \right) = -\eta \delta (1 - \lambda) \tau \eta - \left(\frac{g_{T_t}}{g_{A_t}}\right)^{-2} \sigma \left(\frac{g_{T_t}}{g_{A_t}}\right)^{-2} < 0
\]

and

\[
\frac{d^2}{d\left(\frac{g_{T_t}}{g_{A_t}}\right)^2} \left( \frac{L_{t+1}}{L_t} \right) = \frac{2 \eta \delta (1 - \lambda) \tau \eta - \left(\frac{g_{T_t}}{g_{A_t}}\right)^{-3} \sigma^2 \left(\frac{g_{T_t}}{g_{A_t}}\right)^{-2} + \eta \delta (1 - \lambda) \tau \eta - \left(\frac{g_{T_t}}{g_{A_t}}\right)^{-2} \sigma (\sigma + 1) \left(\frac{g_{T_t}}{g_{A_t}}\right)^{-2} > 0
\]

where we assume \( \eta \tau > \left(\frac{g_{T_t}}{g_{A_t}}\right)^{-\sigma} \) to guarantee the positiveness of second derivative.

Therefore, from period \( t \) to \( t + 1 \), where \( t \in [1, \infty) \), if growth rate of experiment-based technology is greater than growth rate of experience-based technology (i.e. \( g_{T_t} > g_{A_t} \)), the growth rate of human capital (i.e. \( H_{t+1} \)) would increase, in contrast to the reduction in population growth rate (i.e. \( L_{t+1} \)) at the same time. The higher the incremental value of \( g_{T_t} \) relative to \( g_{A_t} \), the higher the growth rate in human capital, \( H_{t+1} \), and the lower the growth rate in population, \( L_{t+1} \), will be, and vice versa. Based on this, we argue that higher value of \( \frac{g_{T_t}}{g_{A_t}} \) causes higher growth rate of human capital, which implies that the level of human capital would increase at a fast pace. At the same time, higher value of \( \frac{g_{T_t}}{g_{A_t}} \) leads to a lower population growth rate. In other words, population level gradually increases slowly but eventually decreases at a rapid pace.
In addition, we let \( g_{H}^{t+1} \) and \( g_{L}^{t+1} \) denote the growth rate of human capital and population growth rate from period \( t \) to \( t+1 \), respectively (i.e. \( g_{H}^{t+1} = \frac{H_{t+1} - H_{t}}{H_{t}} \) and \( g_{L}^{t+1} = \frac{L_{t+1} - L_{t}}{L_{t}} \)). Balanced growth requires that the growth rate of human capital is the same across different periods (i.e. \( g_{H}^{t+1} = g_{H}^{t+2} = g_{H} \), where \( t \in [1, \infty) \)), which also applies to population growth rate (i.e. \( g_{L}^{t+1} = g_{L}^{t+2} = g_{L} \), where \( t \in [1, \infty) \)). Equations (3.3.31) and (3.3.32) show that the balanced growth path in both human capital and population requires that \( \frac{g_{T}^{t+1}}{g_{A}^{t+1}} = \frac{g_{T}^{t+2}}{g_{A}^{t+2}} \) (i.e. \( g_{T}^{t+1} = g_{T}^{t+2} \) and \( g_{A}^{t+1} = g_{A}^{t+2} \), where \( t \in [1, \infty) \)). In other words, the balanced growth path in two types of technology leads to the balanced growth path in both human capital and population.

The proposition and graphs below summarize the dynamics of growth rates for both human capital and population, and the dynamics of the level for both human capital and population.

**Proposition 1** Given that \( \sigma, \delta, \lambda, \tau \in (0, 1), \eta > 0 \) and \( \eta \tau > \left( \frac{g_{T}^{t+1}}{g_{A}^{t+1}} - \sigma \right) \frac{d(H_{t+1} - H_{t})}{d(g_{T}^{t+1} - g_{A}^{t+1})} > 0 \) and \( \frac{d^{2}(H_{t+1} - H_{t})}{d(g_{T}^{t+1} - g_{A}^{t+1})^{2}} < 0; \frac{d(L_{t+1} - L_{t})}{d(g_{T}^{t+1} - g_{A}^{t+1})} < 0 \) and \( \frac{d^{2}(L_{t+1} - L_{t})}{d(g_{T}^{t+1} - g_{A}^{t+1})^{2}} > 0. \)

All figures in this chapter only indicate various general trends of the evolution in terms of human capital accumulation, population growth, technological change and growth in wage income per capita. More specific discussion regarding the degree of increasing or decreasing in such evolution will be considered in future studies.
Figure 1. The effect of growth rates of two technological changes on both population growth rate and the growth rate of human capital

Figure 2. The effect of growth rates of two technological changes on the level of both population and human capital

This proposition simply shows that variations regarding the degree of technological predominance account for the evolution in both human capital and population. Followed by economic development, the invention of technology evolves from the traditional experience-based production towards to more experiment-based production. This results in an initial gradual increase in population growth but eventually a decrease in such growth, while human capital gradually accumulates over time. These implications generally correspond to the evolutionary summary from Galor and Weil (2000) in terms of both population growth and demographic transition.

3.3.2 Dynamics of two types of technology

According to equations (3.2.27) and (3.2.28), dynamic changes in experiment-based tech-
nology $T$ and experience-based technology $A$ are given as follows:

$$\frac{T_{t+1}}{T_t} = \phi T_t^{\alpha - 1} H_t - \frac{1 - \alpha}{\alpha} \tag{3.3.3}$$

$$\frac{A_{t+1}}{A_t} = \mu A_t^{\gamma - 1} L_t^\theta + 1 \tag{3.3.4}$$

From equations (3.3.33) and (3.3.34) together with the balanced growth path (i.e. $g_{t+1}^T = g_{t+2}^T = g^T$ and $g_{t+1}^A = g_{t+2}^A = g^A$, where $t \in [1, \infty)$), we derive

$$\frac{T_{t+1}}{T_t} = \left( \frac{H_{t+1}}{H_t} \right)^{\frac{\gamma}{1 - \alpha}} \tag{3.3.5}$$

$$\frac{A_{t+1}}{A_t} = \left( \frac{L_{t+1}}{L_t} \right)^{\frac{\theta}{1 - \gamma}} \tag{3.3.6}$$

Equations (3.3.5) and (3.3.6) simply reveal that the growth of experiment-based technology and the growth of experience-based technology are positively correlated with the growth of human capital and population growth, respectively. In other words, higher growth of human capital and population result in higher growth of experiment-based technology and experience-based technology, respectively.

By inserting $\frac{H_{t+1}}{H_t}$ and $\frac{L_{t+1}}{L_t}$ from equations (3.3.31) and (3.3.32) provides the results below:

$$\frac{T_{t+1}}{T_t} = \left( \frac{g_t^T}{g_{t+1}^T} \right)^{\sigma} \left( \lambda \eta \delta \right)^{\frac{1}{1 - \alpha}} \tag{3.3.7}$$

$$\frac{A_{t+1}}{A_t} = \left( \frac{g_t^A}{g_{t+1}^A} \right)^{\sigma} \left( \lambda \eta \delta \right)^{\frac{1}{1 - \gamma}} \tag{3.3.8}$$

Therefore, based on equations (3.3.7) and (3.3.8), along the balanced growth path, the rela-
relationship between growth rates of both types of technology is expressed as follow:

\[ g_{t+1}^A = \left[ \frac{\delta(1 - \lambda)}{\tau - (g_{t+1}^T + 1)^{\Lambda - 1}\lambda \delta} \right]^{\frac{\sigma}{\tau - \gamma}} - 1 \]  

(3.3.9)

Given that \( \delta, \lambda, \tau, \theta, \Lambda, \gamma \in (0, 1) \), \( \frac{dg_{t+1}^A}{dg_{t+1}^T} = [\delta(1 - \lambda)]^{\frac{\sigma}{\tau - \gamma}} [\tau - (g_{t+1}^T + 1)^{\Lambda - 1}\lambda \delta]^{-1} (\frac{\theta}{\tau - \gamma})\) \(- (\Lambda - 1)(g_{t+1}^T + 1)^{\Lambda - 2}\lambda \delta] < 0 \), where we assume that \( \tau > (g_{t+1}^T + 1)^{\Lambda - 1}\lambda \delta \) to guarantee the negative result. Accordingly, equation (3.3.9) shows that there exists a negative relationship between \( g_{t+1}^A \) and \( g_{t+1}^T \). In other words, along the balanced growth path, an increase in the growth rate of experiment-based technology would lead to a decrease in the growth rate of experience-based technology, and vice versa.

Moreover, equations (3.3.35) and (3.3.36) show that \( \frac{T_{t+1}^A}{T_t^A} \) and \( \frac{A_{t+1}^A}{A_t^A} \) are positively correlated with \( \frac{H_{t+1}^A}{H_t^A} \) and \( \frac{L_{t+1}^A}{L_t^A} \), respectively. Therefore, the results in the first proposition regarding the effects of \( g_{t+1}^T \) on both \( H_{t+1}^A \) and \( L_{t+1}^A \) are similar to the effects of \( g_{t+1}^A \) on both \( T_{t+1}^A \) and \( A_{t+1}^A \). This can be proven from first and second derivatives with respect to \( g_{t+1}^A \) based on equations (3.3.37) and (3.3.38).

Specifically, given that \( \delta, \lambda, \tau, \theta, \Lambda, \gamma, \sigma \in (0, 1) \) and \( \eta > 0 \), based on equation (3.3.37), the first and second derivatives with respect to \( g_{t+1}^A \) provide that: \( \frac{dT_{t+1}^A}{dg_{t+1}^A} = (\frac{\sigma}{1 - \Lambda})(\frac{g_{t+1}^T}{g_{t+1}^A})^{\frac{\sigma}{\tau - \gamma}} (\lambda \eta \delta) \frac{1}{\tau - \gamma} > 0 \) and \( \frac{d^2T_{t+1}^A}{d(g_{t+1}^A)^2} = (\frac{\sigma}{1 - \Lambda} - 1)(\frac{g_{t+1}^T}{g_{t+1}^A})^{\frac{\sigma}{\tau - \gamma}} - 2(\lambda \eta \delta) \frac{1}{\tau - \gamma} > 0 \), where we assume \( \sigma + \Lambda > 1 \) to ensure the positive result. From equation (3.3.38), two derivatives are given by: \( \frac{dA_{t+1}^A}{dg_{t+1}^A} = [\eta \delta(1 - \lambda)]^{\frac{\sigma}{\tau - \gamma}} (\frac{\theta}{\tau - \gamma})[\tau \eta - (\frac{g_{t+1}^T}{g_{t+1}^A})^{-\sigma} \sigma (\frac{g_{t+1}^T}{g_{t+1}^A})^{-\sigma - 1}] < 0 \) and \( \frac{d^2A_{t+1}^A}{d(g_{t+1}^A)^2} = [\eta \delta(1 - \lambda)]^{\frac{\sigma}{\tau - \gamma}} (\frac{\theta}{\tau - \gamma} - 1)(\frac{\theta}{\tau - \gamma})[\tau \eta - (\frac{g_{t+1}^T}{g_{t+1}^A})^{-\sigma} \sigma (\frac{g_{t+1}^T}{g_{t+1}^A})^{-\sigma - 2}] > 0 \), where we assume \( \eta \tau > (\frac{g_{t+1}^T}{g_{t+1}^A})^{-\sigma} \) to guarantee the positiveness of second derivative.

Therefore, from period \( t \) to \( t + 1 \), where \( t \in [1, \infty) \), if growth rate of experiment-based
technology is greater than growth rate of experience-based technology \( g_{t+1}^T > g_{t+1}^A \), the level of experiment-based technology \( T \) would increase at a fast pace, in contrast to the reduction with a rapid pace in the level of experience-based technology \( A \) at the same time. The higher the incremental value of \( g_{t+1}^T \) relative to \( g_{t+1}^A \) is, the higher for both incremental value of \( T \) and the reduction level of \( A \) will be, and vice versa. We summarize these results in the second proposition together with two graphs illustrating dynamics of technological growth rates.

Proposition 2 Given \( \delta, \lambda, \tau, \Lambda, \gamma, \sigma \in (0,1) \), \( \eta > 0 \), \( \sigma + \Lambda > 1 \), \( \tau > (g_{t+1}^T + 1)^{\Lambda-1} \lambda \delta \) and \( \eta \tau > \left( \frac{g_{t+1}^T}{g_{t+1}^A} \right)^{-\sigma} \), \( \frac{dg_{t+1}^A}{dg_{t+1}^T} < 0 \); \( \frac{d^2g_{t+1}^A}{d^2g_{t+1}^T} > 0 \) and \( \frac{d^2g_{t+1}^T}{d^2g_{t+1}^A} > 0 \); \( \frac{d^2A_{t+1}}{d^2A_{t+1}} < 0 \) and \( \frac{d^2A_{t+1}}{d^2A_{t+1}} > 0 \).

![Graph of Proposition 2](image)

Figure 3. The effect of growth rates of two technological changes on their technological levels.
The implication behind both propositions reveals that changes in growth rates for both experiment-based and experience-based technologies are related to variations in the degree of technological predominance. The gradual transition from experience-based technology to experiment-based technology leads to an increase in the growth rate of experiment-based technology, but a decrease in the growth rate of experience-based technology. Such transition causes the demand for human capital to increase compared with the demand for raw labour (i.e. population). As a result, with more attention focusing on children’s quality rather than quantity, the investment for human capital increases over time, compared with population level which increases but eventually decreases.

3.3.3 Dynamics of per capita wage incomes

According to the wages for human capital and raw labour (i.e. equations (3.3.29) and (3.3.30)), and together with dynamics in both types of technological change (i.e. equations (3.3.37) and (3.3.38)), dynamic changes in wage incomes for both human capital and raw labour are given as follows:

\[
\frac{w_{Ht+1}}{w_{Ht}} = \frac{T_{t+1}}{T_t} = \left[\left(\frac{g_{A t+1}}{g_{T t+1}}\right)^\sigma (\lambda \eta \delta)\right]^{\frac{1}{1-\Lambda}} \tag{3.3.10}
\]

\[
\frac{w_{Lt+1}}{w_{Lt}} = \frac{A_{t+1}}{A_t} = \left[\frac{\eta \delta(1 - \lambda)}{\tau \eta - \left(\frac{g_{T t+1}}{g_{A t+1}}\right)^\sigma}\right]^\frac{\theta}{\gamma} \tag{3.3.11}
\]

We let \(g_{H t+1}^{wH}\) and \(g_{L t+1}^{wL}\) denote the growth rates of wage for human capital and wage for raw labour from period \(t\) to \(t + 1\), respectively (i.e. \(g_{H t+1}^{wH} = \frac{w_{H t+1} - w_{H t}}{w_{H t}}\) and \(g_{L t+1}^{wL} = \frac{w_{L t+1} - w_{L t}}{w_{L t}}\)). Balanced growth requires that the growth rate of wage for human capital is the same across different periods (i.e. \(g_{t+1}^{wH} = g_{t+2}^{wH} = g^{wH}\), where \(t \in [1, \infty)\)), which also applies to the growth rate of wage for raw labour (i.e. \(g_{t+1}^{wL} = g_{t+2}^{wL} = g^{wL}\), where \(t \in [1, \infty)\)). Equations (3.3.40)
and (3.3.41) show that the balanced growth path in wage is reached when \( \frac{g_{T+1}^T}{g_{T+1}^T} = \frac{g_{T+2}^T}{g_{T+2}^T} \) (i.e. \( g_{t+1}^T = g_{t+2}^T \) and \( g_{t+1}^A = g_{t+2}^A \), where \( t \in [1, \infty) \)). In other words, the balanced growth path in technology leads to the balanced growth path in wage.

Equations (3.3.40) and (3.3.41) show that dynamics of wages for human capital and raw labour follows the same pattern as dynamics of experiment-based technology and experience-based technology, respectively. Therefore, our mathematical proof regarding the impact of \( \frac{g_{T+1}^T}{g_{T+1}^T} \) on both \( \frac{w_{t+1}^H}{w_{t+1}^H} \) and \( \frac{w_{t+1}^L}{w_{t+1}^L} \) (i.e. \( \frac{d(w_{H+1}^H)}{d(g_{T+1}^T)} > 0 \) and \( \frac{d^2(w_{H+1}^H)}{d(g_{T+1}^T)^2} > 0 \); \( \frac{d(w_{L+1}^L)}{d(g_{t+1}^T)} < 0 \) and \( \frac{d^2(w_{L+1}^L)}{d(g_{t+1}^T)^2} > 0 \)).

Therefore, from period \( t \) to \( t + 1 \), where \( t \in [1, \infty) \), if growth rate of experiment-based technology is greater than growth rate of experience-based technology (i.e. \( g_{t+1}^T > g_{t+1}^A \)), the growth rate of wage for human capital would increase at a fast pace, in contrast to the decrease at a rapid pace in the growth rate of wage for raw labour at the same time. The higher the incremental value of \( g_{t+1}^T \) relative to \( g_{t+1}^A \) is, the higher for both incremental value of growth rate of wage for human capital and reduction in growth rate of wage for raw labour will be, and vice versa. The proposition and graph below summarize the impact of changes in two technologies on wage incomes for both human capital and raw labour.

**Proposition 3** Given \( \delta, \lambda, \tau, \Lambda, \gamma, \sigma \in (0, 1) \), \( \eta > 0 \), \( \sigma + \Lambda > 1 \), and \( \eta \tau > \left( \frac{\sigma}{\sigma + 1} \right)^{\eta - \sigma} \) and \( \frac{d^2(w_{H+1}^H)}{d(g_{T+1}^T)^2} > 0 \) and \( \frac{d^2(w_{L+1}^L)}{d(g_{T+1}^T)^2} < 0 \) where \( g_{T+1}^T = g_{T+2}^T \).
Figure 4. The effect of growth rates of two technological changes on growth rates of wages for both human capital and raw labour

Figure 5. The effect of growth rates of two technological changes on wage levels for both human capital and raw labour
All three propositions together imply that: when the type of technological change was mainly experience-based, the demand for raw labour (i.e. population) was high which led to high wage payment for such labour, compared with human capital. Thus, parents focused on having more children rather than investing in human capital for each child. As economic development progressed, experiment-based technological change gradually predominates experience-based technological change (i.e. growth rate of experiment-based technological change increases more over time compared with growth rate of experience-based technological change), more technological change transits from experience-based to experiment-based type. Such transition results in an increase in the demand for human capital but a decrease in the demand for raw labour, which led to an increase in the wage payment for human capital but a decrease in the wage payment for raw labour. Motivated by this, parents focused on children’s quality (i.e. human capital) rather than quantity (i.e. having more children). As a consequence, the amount of human capital increased over time and higher demand for human capital led to higher wage payment for human capital in a fast pace. Simultaneously, as more technological progress transit to experiment-based type, lower demand for raw labour resulted in lower wage payment for such labour, and the further decrease in demand for raw labour caused the wage for such labour to reduce even more.

In addition, according to our assumption that each person is not only endowed with an identical amount of raw labour but also receives the same level of education (i.e. the same level of human capital), they contribute raw labour and human capital to the production in different sectors. Thus, for each period \( t \) wage income per capita is represented by the sum between wages for human capital and raw labour (i.e. \( w_{Ht} + w_{Lt} \)).\(^{10}\) According to the effect of growth rates of two technological changes on wages for both human capital and raw

\[^{10}\text{There is no explicit solution regarding the dynamics of wage income per capita in our model, we therefore predict the general trend of such dynamics based on proposition 3.}\]
labour (i.e. proposition 3), we predict that per capita wage income grows at an increasing rate when experience-based technological change predominates experiment-based technological change during the early stage of development. The explanation for this is that at the beginning of economic development, the amount of human capital was low, and hence wage income per capita was mainly contributed by $w_{Lt}$. Higher demand for raw labour led to higher $w_{Lt}$ and hence higher per capita wage income. During technological transition from experience-based to experiment-based type, wage income per capita consisted of two parts (i.e. $w_{Ht}$ and $w_{Lt}$). The trend of wage income per capita during this period is ambiguous, however, as long as the increase in $w_{Ht}$ covers more than the decrease in $w_{Lt}$, wage income per capita still increases. Until now, when technological change is mainly experiment-based, wage income per capita mainly comes from $w_{Ht}$. With further increase in $w_{Ht}$ at a fast pace, wage income per capita experiences the growth at an increasing rate. Therefore, to summarize, if the increase in wage of human capital is more than the decrease in wage of raw labour during technological transition, the general trend of wage income per capita increases and until recently increases at a fast pace, which was firstly due to the increase in wage for raw labour at early economic development and was then contributed by rapid growth in wage for human capital throughout the period of technological transition and modern times.

3.4 Conclusions

Historical data shows that there existed gradual population growth with stagnant income per capita in the pre-modern period, accelerated population growth rate together with increasing growth rate in income per capita after the Industrial Revolution, and the reduction in population growth rate when the growth rate of income per capita increased further. There have been many studies that have tried to address this phenomenon using different mechanisms.

\[\text{This can be tested in our future simulation analysis.}\]
This chapter develops this further by establishing a holistic model taking different patterns of technological change, which are based on endogenous growth theory, from pre-modern to modern times into consideration.

This chapter studied the dynamic evolution of technological change, per capita wage income growth, population growth and human capital accumulation in the process of economic development. Our model showed that, during technological transition, variations in the combination between growth rates of two types of technological change accounted for the evolution in human capital accumulation, population growth and per capita wage income from pre-modern to modern times.

Our results highlight that growth rates for both experiment-based and experience-based technological changes reflect the extent of technological predominance. The gradual transition from experience-based to experiment-based types results in an increase in the growth rate of experiment-based technological change, but a decrease in the growth rate of experience-based technological change. In response to a higher growth rate of experiment-based technological change compared with growth rate of experience-based technological change, growth rate of human capital increases but population growth rate decreases, which causes the growth rate for wage of human capital to increase but the growth rate for wage of raw labour to decrease over time. Per capita wage income grows, especially until recently, it grows in a fast speed as a response to the technological progress over time. These results generally match the historical evidence on both demographic change and income per capita as shown in the stylized facts.

3.5 Appendix

This section lists historical facts regarding the evolution in the interaction among technological change, population growth, human capital accumulation and income per capita through-
out human history. We categorize this entire evolution into three parts, based on Galor and Weil (2000), where economic progress was formed by three different regimes: the Malthusian Regime, the Post-Malthusian Regime, and the Modern Growth Regime. All evidences here are quoted from historical facts in Galor (2005).

3.5.1 The Malthusian Regime

The Malthusian stagnation dominated the whole world during most of human history. There was little change in technological development and population growth, compared with modern development. Both technological development and land expansion mainly led to an increase in population level, whereas income per capita remained almost stationary.

Income per capita

As shown in figure A1, during the first millennium, there was no obvious change in the average level of world income per capita, which was about $450 each year, and its average growth rate was virtually zero. This was because of slow technological development and also the increase in income per capita eventually led to the expansion in population growth. The knot of Malthusian trap was broken at the end of the 18th century. The average level of world income per capita from the year 1000 to 1820 was less than $670 each year, and its average growth rate during this period was around 0.05% each year (Maddison, 2001).
Specifically, all areas in various parts of the world were trapped within the Malthusian stagnation. Figure A2 shows that: among Asia, Africa, Eastern and Western Europe, Western Offshoots (i.e. Canada, Australia, United States and New Zealand) and Latin America, the average income per capita in the rst millennium fluctuated between $400 and $450 each year and their average growth rates were almost close to zero. However, at the end of the 18th century, the Malthusian Trap in various regions was no longer in existence. In the year 1820, income per capita among Africa, Asia, Eastern Europe, Latin America and the Western offshoots and Western Europe were: $418 each year, $581 each year, $683 each year, $692 each year, $1202 each year, and $1204 each year, respectively. The average growth rate of income per capita in the poor area of Africa was 0% and the average growth rate in the rich area of Western Europe was 0.14%.
Figure A2. The Evolution of Regional Income Per Capita over the Years 1 - 2001. Sources: Maddison (2003)

Income Level and Population Growth

Figures A3 illustrates that there was a small increase in the world population during the rst millennium. The population number increased from 231 million during 1 AD to 268 million during 1000 AD.

Figure A3. The Evolution of World Population and Income Per Capita over the Years 1 - 2000. Source: Maddison (2001)

Based on figure A4, the average growth rate of population was 0.02% each year in the
first millennium. The world population increased by 63% from the year 1000 to 1500 (i.e. from 268 million to 438 million). During this period, the average population growth rate each year was 0.1%. Between the year 1500 and 1820, the world population increased further by 138% (i.e. from 438 million to 1041 million). The average growth rate was 0.27% each year. During the last two centuries, there still existed a positive correlation between income per capita and population level, where the world population increased to almost 6 billion people. Within the Malthusian Regime, as income per capita gradually increased, the average growth rate of world population increased as a result. This positive correlation existed within and throughout different countries.

Figure A4. Population Growth and Income Per Capita in the World Economy. Source: Maddison (2001)

3.5.2 The Post Malthusian Regime

The Post Malthusian Regime was characterized by an evident increase in the rate of technological development together with industrialization, which led to an escape from the Malthusian Stagnation. As shown in Figures A1, A2 and the following figure A5, over this period, although there existed an obvious and significant increase in the growth rate of income per capita, this also led to a large increase in population growth reflected in Figures A6 and
A7, and eventually reduced the potential increase in income per capita. Thus, as technological progress started to accelerate, the growth of income was partially matched by an increase in population growth and income per capita gradually increased during the Post Malthusian Regime.

Figure A5. Fluctuations in Real GDP Per Capita: England, 1260-1870. Source: Clark (2001)

Figure A6. The Evolution of World Population and Income Per Capita over the Years 1-2000. Source: Maddison (2001)
In the Post-Malthusian Regime, there was an obvious and significant increase in average growth rate of income per capita, and substantial differences in standards of living began to appear in various countries. Figure A1 illustrates that the average growth rate of world income per capita increased from 0.05% each year during the period between the year 1500 and 1820 to 0.53% each year between 1820 and 1870, and 1.3% each year between 1870 and 1913.

Income and Population Growth

During the Post-Malthusian Regime, income per capita increased rapidly, a proportion of which had led to an increase in population level. The Malthusian theory which considered the positive correlation between higher income and higher population growth still took place. Nevertheless, the Malthusian Stagnation was no longer in existence. Due to the increasing pace of technological development and capital accumulation, income per capita increased, although there still existed a certain degree of the offsetting effect on income per capita caused by the increase in population level.
There was a drastic increase in population growth between the Western European and the Western Offshoots, which eventually caused a modest increase in the world population growth. Following on from this, the increase in population growth within less developed regions led to a significant increase in the world population growth. The average of world population growth rate changed from 0.27% each year between the year 1500 and 1820 to 0.4% each year between the year 1820 and 1870, and to 0.8% each year between the year 1870 and 1913.

In addition, between the end of the 19th century and the beginning of the 20th century, although there existed a reduction in population growth in both the Western offshoots and Western Europe, income per capita in less developed regions significantly increased before the demographic transitions. This led to a further rise in the world population growth rate to 0.93% each year during the time interval 1913-1950, and then a drastic increase to 1.92% each year during the years 1950-1973. Eventually, population growth rate gradually decreased to 1.66% each year between 1973 and 1998. This was due to the demographic transition within less developed regions during the second half of the 20th century (Maddison, 2001).
Growth in Income Per Capita and Population Growth

Figure A8. Regional Growth of GDP Per Capita and Population: 1500-2000. Source: Maddison (2001)

Figure A8 shows that there existed a positive relationship between population growth and growth rate of income per capita across all regions in the world. For instance, in Western Europe, the average growth rate of income per capita increased from an annual rate of 0.15% between the periods 1500 and 1820 to the rate of 0.95% during the period between 1820 and 1870. In the meantime, there was also a noticeable rise in population growth from an annual rate 0.26% between the year 1500 and 1820 to the rate of 0.7%. Furthermore, in the Western Oshotts, the average growth rate of income per capita increased from the annual rate of 0.34%
during the times 1500-1820 to 1.42% between the year 1820 and 1870. Population growth significantly increased from the annual rate of 0.43% over the years 1500-1820 to 2.87%. Moreover, in Latin America, the growth rate of income per capita increased from the annual rate of 0.1% between 1820 and 1870 to 1.81% during the period 1870-1913, and then at the rate of 1.43% during the period 1913-1950 and 2.52% over the years 1950-1973. In the meantime, population growth increased significantly to the annual rate of 1.64% between 1870 and 1913, 1.97% over the period 1913-1950, and 2.73% during the time 1950-1973. Africa’s average growth rate of income per capita increased from the annual rate of 0.12% over the time 1820-1870 to 0.64% between 1870 and 1913, and later on at 1.02% during the period 1913-1950 and 2.07% over the years 1950-1973. Population growth increased monotonically from the annual rate of 0.4% between 1820 and 1870 to 0.75% between 1870 and 1913, 1.65% during the period 1913-1950, 2.33% over the years 1950-1973, and 2.73% during the years 1973-1998.

Industrialization and Urbanization

Both the increase in the pace of the development of industrialization and the significant increase in urbanization symbolized the take-off from the Malthusian Regime for less developed and developed economies.

In terms of Industrialization, in developed regions, the rapid development of industrialization broke the Malthusian knot. Figure A9 illustrated that, in the United Kingdom, there existed a significant rise in per-capita level of Industrialization (i.e. per capita amount of industrial production) since 1750, increasing by 50% between the year 1750 and 1800, quadrupling during the period 1800-1860, and almost doubling between the year 1860 and 1913. In the United States, per-capita level of industrialization doubled over both periods between 1750-1800 and 1800-1860, and increasing by six times over the time interval 1860-1913. Similarly, in Germany, France, Sweden, Switzerland, Belgium, and Canada, industrialization almost
doubled between the year 1800 and 1860, and accelerating even more during the period 1860-
1913. In addition, in the 20th century, increased industrialization is also related to the take-o
from Malthusian Regime across less developed regions. Nevertheless, figure 10 shows that the
less developed regions suffered from an reduction in per capita industrialization over the 19th
century.

![Per Capita Levels of Industrialization](image.png)

Figure A9. Per Capita Levels of Industrialization. Source: Bairoch (1982)

Early Stages of Human Capital Accumulation

The human capital accumulation over the Post Malthusian Regime was due to both accel-
eration in technological development and rise in income per capita. The rise in real wage and
income per capita loosened the budget constraint for each household gradually, and moreover,
the demand for human capital increased over this period. Particularly, there was a rise in skill
requirement, which was associated with an increase in the demand for education (i.e. human
capital) during the second phase of the Industrial Revolution. These facts resulted in a rise in
human capital investment (i.e. education).

In England and Wales, years of schooling increased from 2.3 during the period 1801-1805
to 5.2 over the period 1852-1856 (Matthews et al., 1982). Across less developed regions, there
was also a gradual rise in human capital accumulation over the process of industrialization.
Barro and Lee (2000) stated that, during the Post Malthusian Regime, there was a significant rise in education in less developed economies. In Latin America, years of schooling rose from 3.5 within 1960 to 4.4 during 1975. In Sub-Saharan Africa, years increased from 1.6 within 1960 to 3.4 during 2000. In South Asia, years increased from 1.4 during 1960 to 1.9 during 1975.

3.5.3 The Modern Growth Regime

During industrialization in the Post Malthusian Regime, the rise in technological development rate and together with human capital accumulation stimulated the demographic transition, which prepared for the transition to the Modern Growth Regime. During the period of post demographic transition, the increase in total income caused by the interaction between technological development and human capital accumulation was reflected in the continuous increase in income per capita rather than in population growth. In developed economies, like the Western Offshoots and Western Europe, the transition to the Modern Growth Regime took place towards the end of the 19th century. Some less developed countries in Asia and Latin America, the transition took off towards the end of the 20th century. However, it was difficult for Africa to make this change.

Growth of Income Per Capita

There was significant growth in the average growth rate of income per capita and also reduction in population growth during this period. The interaction between increasing pace of technological development and the increasing demand for human capital stimulated the demographic transition across Western Offshoots, Western Europe, and some countries within less developed regions. This allowed continuous rise in income per capita. Figure A10 illustrates that, during the last century, the growth rate of income per capita was around 2% each year between the Western Offshoots and Western Europe.
Nevertheless, across some less developed economies, the continuous growth in income per capita only occurred during the last decades. Figure A11 shows that Asia’s growth rate of income per capita was stable during the last 50 years. In Latin America, the growth rate reduced during this time period. For Africa, there was no increase over the last few decades.

Between both developed and less developed economies, the transition to the Modern Growth Regime was associated with the fast pace development of industrialization. Figure
A9 shows that per capita Industrialization (i.e. per capita amount of industrial production) doubled during the period 1860-1913 and tripled during the 20th century. In the United States, per capita industrialization rose by six times between the year 1860 and 1913, and tripled in the 20th century. Among Germany, France, Sweden, Switzerland, Belgium, and Canada, there was a significant rise in industrialization between the year 1860 and 1913 and during the rest of the 20th century. In less developed countries, which transited to the Modern Growth Regime during recent decades, there was a significant rise in industrialization.

In the Modern Growth Regime, human capital accumulation rises gradually compared with physical capital and fertility rate reduces drastically. During the first phase of the Industrial Revolution (i.e. 1760-1830), there existed a significant rise in capital accumulation, which was regarded as a share of GDP. However, the requirements for both skills and literacy were low. The government did not encourage the improvement in literacy, and on-the-job training was the main channel to gain skills (Green 1990, and Mokyr 1990, 1993). There was no growth in literacy rates over the time interval 1750-1830 (Sanderson 1995).

During the second phase of the Industrial Revolution, the requirement of skills played an important part in production and there was an obvious rise in education level. The rate of educational investment rose from 6% during 1760 to 11.7% within 1831, about 11% during the period 1856-1913 (Crafts, 1985; Matthews et al, 1982). For instance, figure A12 illustrates that, in England, income per capita increased significantly in 1865, and the schooling for 10 year old children increased from 40% during 1870 to 100% during 1900. However, fertility Rate in England reduced drastically from around 5 per household during 1875 to about 2 during 1925. In the United States, human capital accumulation gradually increased compared with physical capital. During the years 1890-1999, human capital accumulation made a great contribution to the US growth (almost doubled). However, there was an reduction in the contribution from physical capital. Goldin and Katz (2001) provides that, between the year 1890 and 1915, the
growth rate of educational productivity was 0.29% each year, and this contributed to 11% of annual growth rate of income per capita. Between the year 1915 and 1999, the educational productivity growth rate was 0.53% each year, which led to 20% of annual growth rate of income per capita. Abramovitz and David (2000) documented that the contribution of physical capital accumulation to the income per capita growth rate reduced from 56% during the period 1800-1890 to 31% over the time interval 1890-1927 and 21% between the year 1929 and 1966.

Figure A12. The Sharp Rise in Real GDP Per Capita in the Transition to Sustained Economic Growth: England 1870-1915. Source: Clark (2001) and Feinstein (1972)

The Demographic Transition

During the last century, demographic transition occurred throughout the world. Compared with the trend of population growth over the Post Malthusian Regime, there existed an reduction in population growth and fertility rate caused by a demographic transition across regions in the world. The increased human capital accumulation and technological development were associated with an increase in income per capita.

Regarding the decline in population growth, the take-off of demographic transition varies among different regions. Figure A13 shows that, in Western Europe, the Western Oshoots and Eastern Europe, population growth declined towards the end of the 19th century. Population
growth rate in Latin America and Asia reduced in the last decades of the 20th century. In Africa, population growth continues increasing, but it is possible to decrease in future because of the reduction in fertility rate starting from the 1980s. Population growth reduced in the Western Offshoots from the annual rate of 2.87% over the years 1820-1870 to 2.07% during the period 1870-1913 and 1.25% between the year 1913 and 1950. In Western Europe, there was a significant reduction in population growth from 0.77% each year over the time interval 1870-1913 to 0.42% each year during the period 1913-1950. Eastern Europe followed the similar pattern of decline. Population growth in both Latin America and Asia declined during the 1970s. Although there was an reduction in fertility rate in Africa, population growth continues increasing. In Latin America, population growth reduced from the annual rate of 2.73% over the years 1950-1973 to 2.01% during the period 1973-1998. In Asia (excluding Japan), population growth reduced from the annual rate of 2.21% over the years 1950-1973 to 1.86% during the period 1973-1998. In Africa, population growth rate rose from the annual rate of 0.4% during the period 1820-1870 to 0.75% between the year 1870 and 1913, 1.65% over the time interval 1913-1950, 2.33% during the period 1950-1973, and 2.73% over the time interval 1973-1998. As a result, the population in Africa rose by 41% during 60 years (i.e. from 7% during 1913 to 9.9% during 1973; extra 30% during the last 25 years, from 9.9% during 1973 to 12.9% during 1998).
In terms of fertility decline, the reduction in population growth was associated with the reduction in fertility rate. Figure A14 shows that, during the period 1960-1999, there exited a drastic reduction of fertility rate in Latin America from 6 to 2.7 and in Asia from 6.14 to 3.14. In Western Europe, the fertility rate reduced from 2.8 during 1960 to 1.5 during 1999. In the Western Oshoots, the rate reduced from 3.84 during 1960 to 1.83 during 1999 (World Development Indicators, 2001). There also existed an reduction in Africa’s fertility rate from 6.55 during 1960 to 5.0 during 1999. In Western Europe, the demographic transition took place towards the turn of the 19th century. During the 1870s, several economies suffered from a drastic reduction in fertility. This caused an reduction in fertility rate by 1/3 in different countries in a 50 year period.

Figure A15 illustrates that, during the demographic transition, there existed an reduction in the crude birth rates and a significantly decrease in the Net Reproduction Rate (i.e. the quantity of daughters for each woman reaching the reproduction age). In England, Crude Birth Rates reduced by 44% between the year 1875 and 1920. Crude Birth Rates in Germany reduced by 37% during the period 1875-1920. In Sweden, Crude Birth Rates reduced by 32% between the year 1875 and 1920, and Finland’s rates reduced by 32% over the time interval 1875-1920. There was a decline in fertility in France in the second half of the 18th century (i.e. between the year 1865 and 1910). The Crude Birth Rates in France reduced by 26% over the period 1965-1910.
Figure A15. The Demographic Transition in Western Europe: Crude Birth Rates and Net Reproduction Rates. Source: Andorka (1978) and Kuzynski (1969)

Figure A16 illustrates that, in Western Europe, Total Fertility Rates (TFR) reached to a highest point during the 1870s and followed by a significant reduction among Western European States. TFR in England reduced by 51% (i.e. from 4.94 children during 1875 to 2.4 during 1920). TFR in Germany reduced by 57% (i.e. from 5.29 during 1885 to 2.26 during 1920). In Sweden, TFR reduced by 61% (i.e. from 4.51 during 1876 to 1.77 during 1931), the reduction of 52% in Finland (i.e. from 4.96 during 1876 to 2.4 during 1931). France suffered from a huge reduction over years 1750-1850 and there also existed an extra reduction from 3.45 during 1880 to 1.65 during 1920.
Industrial Development and Human Capital Formation

During the course of industrialization, the requirement for human capital in production started to rise gradually. The increased growth rate in technological development led to a gradual increase in human capital demand, and hence in educational investment. This had a positive circular effect on further technological progress. Human capital accumulation in both developed and less developed economies took place before the demographic transition. This implies that both the demographic transition and the transition to the Modern Growth Regime were mainly affected by the increase in human capital demand and hence in human capital accumulation during industrialization.

In developed regions, there was little effect of human capital on production during the rst phase of the Industrial Revolution. Nevertheless, during the second phase, there was an obvious rise in human capital demand. The requirement for skilled workers increased during industrialization, which affected the educational investment and hence in human capital accumulation. Compared with the effect of income on population growth during the Malthusian Regime, investment in each child increased during the demographic transition. For instance, there was an increase in the literacy rate for men from about 65% during the rst phase of the Industrial Revolution to almost 100% at the last stage of the 19th century (Clark, 2003). Furthermore, there was an increase in primary school children aged between 5 and 14 from 11% during 1855 to 74% during 1900. Other European countries followed the similar pattern (Flora et al, 1983). For instance, figure A17 shows that, in France, primary school children aged between 5 and 14 increased from 30% during 1832 to 86% during 1901 over the second phase of industrialization.
Figure A17. The Fraction of Children Age 5-14 in Public Primary Schools, 1820-1940
Source: Flora et al. (1983)

Moreover, the reformation in education of developed economies between the 18th and 19th centuries affected the development in human capital and hence in the demographic transition during the second half of the 19th century. In England, during the rst phase of the Industrial Revolution (i.e. from 1760 to 1830), there was little supply of human capital. There was no obvious change in literacy rates. The literacy requirement for production was only 4.9% for men and 2.2% for women during 1841 (Mitch 1992, pp. 14-15). By contrast, during the second phase of the Industrial Revolution, human capital demand increased significantly and primary school children aged between 5 and 14 rose from 11% during 1855 to 25% during 1870 (Flora et al. 1983). The demand for literacy increased over the 1850s (Mitch 1993, p. 292). Schooling for 10 years old children rose from 40% during 1870 to 100% during 1900. The literacy rate for men rose from 65% during the rst phase of the Industrial Revolution to almost 100% at the end of the 19th century (Clark 2002). Primary school children aged between 5 and 14 rose from 11% during 1855 to 74% during 1900 over the second half of the 19th century (Flora et al, 1983). In France, primary school children aged between 5 and 14 rose from 51.5% during 1850 to 86% during 1901 (Flora et al, 1983). In the United States, Abramowitz and David (2000)
and Goldin and Katz (2001) argued that almost doubled contribution to the US growth was caused by human capital accumulation during the time interval 1890-1999. Public secondary schools enrollment rose 70-fold between the year 1870 and 1950 (Kurian, 1994).

In less developed economies, human capital also gradually rose during industrialization. Figure A17 illustrates that there existed an increase in educational investment throughout all less developed economies. During the 19th century, while there was an increase in educational investment, the total fertility rate decreased. For instance, years of schooling in Africa rose by 44% (i.e. from 1.56 to 2.44) before the reduction in total fertility rates during 1980, which is shown in figure A16.

Figure A18. The Evolution of Average Years of Education: 1960-2000. Source: Barro and Lee (2000)
References


Varvarigos, D., and Zakaria, I.Z., 2013, Endogenous fertility in a growth model with public


Chapter 4

Conclusion

Since early economic development, wage inequality has always been regarded as the long term challenge all around the world. Many economists have tried to explain wage inequality within one country through different perspectives (e.g. technological change). However, the area, which considers the effect of technological change on the wage gap between people from various countries but with the identical skill level, has not been thoroughly researched. Such international wage inequality has many important roles in, for instance, reflecting international unfairness, measuring the difficulties for development policy and measuring the inefficiency of allocating labour or capital across the world. Therefore, it is essential to investigate the cause of this type of international inequality, which helps to understand and hence to control these aspects more effectively (Rosenzweig, 2010).

By taking this into consideration, chapter 2 contributes to the existing literature by providing a general equilibrium model which is able to account for both domestic and international wage inequalities, with a special emphasis on the role of technological change. Specifically, according to both existing studies and evidence relating to the effect of technological change on labour productivity and international transportation costs, we introduced a new categorization of total technological change: productivity enhancing and transportation cost reducing technological changes. We then incorporated these two types of technological change into an open
trade economy encompassing one developed and one developing country, where each owns both skilled and unskilled labour. Within our framework, we learned that wage inequality within one country, whether developed or not, is determined by its own share of productivity enhancing and transportation cost reducing technological change, and simultaneously, the impact of such technological share on domestic wage inequality varies depending on whether the impact of productivity enhancing technological change has a greater positive impact on increasing the productivity of skilled or unskilled workers. Our results regarding the impact of domestic technological change on wage inequality within the same country are in line with the principle of either skill-biased or unskill-biased technical change, and also explain existing facts regarding the impact of trade cost on domestic wage inequality.

Moreover, regarding international wage inequalities of workers with the same/similar skill level but in two different countries, we learned that such international wage inequalities are determined by the share of productivity enhancing and transportation cost reducing technological change in both countries, and the impact of such technological share on international wage inequalities also depends on whether productivity enhancing technological change in both countries has a greater impact on increasing the productivity of skilled or unskilled workers. Our analysis of international wage inequality complements the relevant study by Acemoglu, Gancia and Zilibotti (2015), where they only considered the determinant for reducing international wage inequalities. We adopted the idea of different types of technological change to explain not only the decrease but also the increase in international wage inequality.

In addition, the model in chapter 2 can be regarded as a benchmark analysis regarding the effect of technological change on both domestic and international wage inequalities, since our theoretical framework favours the relevant existing literature by providing a holistic analysis encompassing the impact of technological change on both inequalities, which has not been investigated before. However, in a sense, the assumptions of our model are restrictive, which
could be considered to be more practical. Therefore, our model has left plenty of fruitful and potential areas for future studies. To enrich our model, one possible extension could allow the technological spillover between sectors or countries. In addition, due to the fact that technological change has an impact on reducing transportation costs, which also improves trade activities, in particular, outsourcing and off-shoring, it is possible to incorporate such activities into our framework to analyze wage inequalities both domestically and internationally more effectively. Moreover, in the present paper, the allocation of each type of technological change is assumed to be exogenous. It is possible to endogenize this and hence provide a more sophisticated model to tackle both domestic and international wage inequalities. Empirically, possible simulation based on the data from one developed and one developing country, for example, the United States and China, would be feasible to check the robustness of our findings.

As for the potential research in policy implications, one could incorporate the tariff on import products into our framework. The government can increase the tariff, which discourages the production of transportation cost reducing technology and hence increases the transaction cost in an open economy. The idea is to reduce the consumption of foreign produced goods and to increase the consumption of home produced goods. Accordingly, all or part of the jobs for unskilled workers at home would be secured. For example, the US government increases the tariff on oil and the Chinese government increases the tariff on brass to protect domestic unskilled workers. In addition, according to our findings regarding the impact of technological change on exchange rate, this could be associated with the efficiency of implementing trade policy, which can be regarded as another fruitful area to explore in future.

Regarding the evolution in demographic change and income growth, it has always been regarded as a challenge to set up a unified framework to explain such evolution encompassing various stages of economic development throughout human history. This is important, since a single framework would help understand the underlying phenomena and provide more effective
testable predictions and improve the analysis on the impact of policy interventions (Galor and Weil, 2000).

With this in mind, chapter 3 establishes a unified overlapping generations model to account for the evolution in technological change, population growth, human capital accumulation, and the growth in income per capita throughout different periods of economic development. Existing literature only considers the impact of overall technological change on such evolution. Our framework therefore contributes to the literature by firstly categorizing technological change based on the endogenous growth theory and then considers the impact of each technological change on such evolution, which provides a complementary analysis to the relevant studies.

The key component in our framework is technological change, where, depending on how technology is invented based on endogenous growth theories, we have distinguished that there exists broadly two types of technological change, one is experience-based which has a positive relationship with population level and the other is experiment-based which is positively affected by the level of human capital. Technological change during the early stage of development was mainly experience-based, compared with the majority of experiment-based technological change in modern times. We find that this gradual transition (i.e. an increase in the growth rate of experiment-based technological change but a decrease in the growth rate of experience-based technological change over time) has a direct impact on the evolution in both demographic change and income growth from pre-modern to modern days. Our dynamic results on population growth, human capital accumulation and the growth in income per capita are generally consistent with relevant empirical evidence throughout different stages of economic development.

In addition, although the framework in chapter 3 provides a complementary analysis to the relevant literature, the assumptions of our model are somewhat restrictive, which leads to
many possibilities to enrich our model and hence paves the way for many possible future studies. For instance, our model only allows each final goods sector to use a certain type of technology to produce. This is purely for the purpose of simplifying calculation. However, it is possible to let each final goods sector adopt two different types of technologies, which is more realistic, and would allow our theoretical results to be examined for any changes. Empirically, due to mathematical infeasibility, our model is unable to generate a specific numerical result regarding the dynamic change in income per capita. However, this can be solved when simulating our model, which would generate dynamics of both population growth and the growth in income per capita, and in turn the robustness of our results can be verified.