THREE ESSAYS CONSIDERING HUMAN CAPITAL COMPOSITION AND ECONOMIC GROWTH

A Dissertation
Submitted to
the Temple University Graduate Board

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in Partial Fulfillment
of the Requirements for the Degree of
DOCTOR OF PHILOSOPHY

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by

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May, 2017

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ABSTRACT

Human capital has long been recognized as a crucial determinant of economic development. The main contribution of my dissertation is to both theoretically and empirically demonstrate the idea that the composition (different types of education) of human capital determines technological progress and affects long-run economic growth. As compared to traditional human capital and growth literature, it emphasizes the composition effect of human capital, rather than the level effect, on economic development. It provides a new perspective in characterizing the stages of economic development along the growth path. Optimal human capital composition benefits not only lesser developed countries who usually lack educational resources but also developed countries with limited population growth potential.

The first chapter, titled "Education, Technology, Human Capital Composition and Economic Development", develops a framework of endogenous educational decisions and technological progress to explore the human capital composition and its effects on economic growth. In this model, growth is driven by technological advancement, which depends on the human capital composition. Individuals can choose from different types of workers: unskilled workers, generalists or specialists. Both generalists and specialists, through technological progress, are able to enhance growth. The model considers the role of technology stock, coordination cost, education cost and worker's innate ability on the human capital composition and economic growth. The main result shows the improvement in the composition of human capital promotes economic growth in most economic stages. However, this positive effect tapers off as the economy reaches complete specialization. This provides a possible explanation for the convergence of economic growth to zero asymptotically in the long run.

I extend the argument into an open economy framework in the second chapter,

titled "Migration Effects on Home Country's Composition of Human Capital and Economic Development". This chapter examines migration effects on domestic composition of human capital and economic growth. The net effect of migration depends on two facets. On one hand, the possibility of migration provides incentives for workers to invest in education and consequently increases the fraction of skilled workers in home country's human capital composition. On the other hand, increased population of skilled emigrants hinders the accumulation of human capital. A sufficient condition for beneficial migration is derived: if the ex ante domestic fraction of unskilled worker is relatively high, allowing the home country to achieve faster economic growth with migration.

The last chapter, titled "The Effect of Tertiary Education Composition on Economic Growth", differentiates types of tertiary education by ISECD levels and empirically investigates their effects on economic growth. I use panel data on a group of 77 countries for the period 1998-2011. In dynamic panel data estimation, a potential endogeneity bias could arise due to the inclusion of lagged dependent variables. Several methods are applied to overcome the issue, such as Anderson-Hsiao estimator, the Difference Generalized Method of Moments estimator and the System Generalized Method of Moments estimator. The study shows a significantly positive relationship between short-cycle tertiary education and real GDP per capita for both developed and developing countries. However, undergraduate and graduate education only positively correlate to economic growth in developed countries. The empirical results are informative for developed countries as well as developing countries. Understanding the contribution of tertiary education in different levels allows them to effectively allocate resources and appropriately integrate it in growth policies.

For my mother and father.

ACKNOWLEDGEMENTS

First and foremost I would like to express the deepest appreciation to my advisory chair Dr. Moritz Ritter. It has been an honor to be his Ph.D. student. I sincerely appreciate all his contributions of time, ideas, support and guidance. This dissertation would not have been written without his efforts.

I am grateful for the immense help from the members of my committee: Dr. Charles Swanson, Dr. Douglas Webber and Dr. Pedro Silos. Their insightful feedback and encouraging support consistently motivates me to improve my work.

I would like to acknowledge the Department of Economics at Temple University. My graduate experience benefited greatly from the courses I took, the teaching experience I had and the opportunities to serve as a teaching assistant for Dr. William Holmes and Dr. Donald Wargo. I am also grateful for the funding sources that made my Ph.D. work possible.

During my five years at Temple Institutional Research and Assessment Center, it has been a source of friendships and collaboration. I would like to thank my supervisor Gina Calzaferri and many other colleagues for their thoughtfulness and kindness.

My time at Temple was made enjoyable due to many friends and classmates that became part of my life. I am grateful for such a great journey with so many wonderful memories as I finished up my degree. Huilin Zhu, Tao Jin, Xinyi Li, Fangzheng Geng, Yuebing Hong, Lulei Song and Xiyue Cao made my time here at Temple a lot more fun.

Lastly, I would like to acknowledge my family who supported me all the way. I could not have reached to this point without them. I am grateful to my uncle Yangjing for his continuous support. I am forever indebted to my parents for giving

me the opportunities that have made who I am. I have been blessed in my life to have their unparalleled love and support, and I dedicate this milestone to them.

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CHAPTER 1

EDUCATION, TECHNOLOGY, HUMAN CAPITAL COMPOSITION AND ECONOMIC DEVELOPMENT

1 Introduction

The accumulation of human capital is well recognized as a key determinant in economic growth through technological imitation and innovation (Nelson and Phelps, 1966). In empirical and theoretical research on human capital, scholars have been seeking to explore the linkage between economic development and human capital (Schultz, 1961; Romer, 1986; Lucas, 1988; Mulligan and Sala-i-Martin, 1992). Although the growth effect of human capital has been extensively studied, the empirical results are not conclusive (Barro, 1991; Mankiw et al., 1992; Benhabib and Spiegel, 1994; Krueger and Lindahl, 2001). A possible explanation for the inconclusive results is that despite the level effect of human capital per se, the effect of different compositions of human capital (different types of education) on economic growth is nonidentical and significant (Grossman and Helpman, 1991). Larger countries with more investment in human capital are not guaranteed to grow faster than smaller countries with proper compositions of human capital.[1]

[1] In 2014, OECD countries have an average 4.8% of gross national income (GNI) in education expenditure and the average growth rate of GDP per capita is 1.2%, specifically Belgium with 6.1% of GNI on education but only 0.9% in growth, and Italy with 3.9% of GNI spent in education while having the growth rate of -1.35%. A number of South Asia countries, notably Bangladesh, India

This paper theorizes the formation of human capital composition through endogenizing educational decision and technological progress, which is the engine of long-run economic growth, in economic growth. I specifically focus on the composition effect of human capital, instead of its level effect, on productivity growth and economic development in four different equilibria from a stagnated economy to a fully specialized economy. Individuals make decisions about education based on various factors, such as their innate abilities as well as the existing average technology level, to become heterogeneous workers. In this growth model, the technological innovation is advanced by skilled workers (generalists and specialists). The results show that both generalists and specialists are growth-enhancing and the growth rate depends on the relative fractions of three types of human capital as well as the existing average technology level. As an economy moves towards a complete division of labor, its growth rate gradually decreases which implies economic convergence.

Human capital is typically treated as homogeneous; while recent studies suggest that there is a complementary effect of different types of human capital, which can greatly affect economic development.[2] Modern production requires a variety of expert knowledge in a single product. From smart phones to LED televisions, from hybrid cars to airplanes, from high tech running shoes to organic foods, it is not uncommon that people in different fields come together to cooperate in innovation when the knowledge stock is too great and it is almost impossible for one person to acquire the advanced knowledge of the whole production. In fact, it is possible that a certain type of worker (e.g. educated worker) is more substitutable for physical capital than other types (e.g. unskilled worker) in certain tasks. Thus, the composition effect of human capital is based on Smith's foundational theory that specialization achieves

and Pakistan, which have 1.6%, 3.1% and 1.8% of GNI on education expenditure with 4.8%, 5.9% and 2.6% in growth respectively, have invested less in human capital while achieving higher growth rates.

[2]See Ljungberg and Nilsson (2009), Manca (2009) and Islam (2010).

high productivity. Division of labor makes technology imitation and innovation easier and more efficient.

In line with growth literature, the long-run economic growth is driven by endogenous technological progress which is determined by the accumulation of human capital. An economy endowed with a larger technology stock tends to encourage workers to invest more in education. This, in return, assures a higher growth rate in technology to generate an even larger stock. However, in contrast to the traditional form of human capital as a basic input, the effect of human capital in this model does not directly enter into the production function but through its role in technological progress, which helps to focus on the composition effect of human capital on growth.

The model in this paper demonstrates the composition of human capital by three types of workers: unskilled workers, generalists and specialists. An unskilled worker does not contribute to technological progress; a generalist innovates on his own and improve technology with modest knowledge in multiple fields; a specialist with deep knowledge in a particular field requires the cooperation with another specialist who is adept in a complementary field in innovation. Composition differences emerge through workers' education decisions in which each worker chooses to become one type to maximize his consumption depending on his internal ability and external economic factors.

To determine the composition effect of human capital on economic growth, the model characterizes different stages of economic development by four equilibria. First, an unskilled equilibrium contains only unskilled workers in a labor force when technology level is extremely low and even the 'upper tail' of workers find it hard to be profitable as a generalist or a specialist. This equilibrium can cause a 'poverty trap' in poor countries to have stagnated economies. Next, a generalist equilibrium is when some of the unskilled workers become skilled workers but they only choose to be generalists. This equilibrium can be properly categorized into Rostow's second stage of economic growth where initial technology breakthroughs most likely arise from external intrusion and then the economy grows endogenously.[3] Third, a mixed equilibrium includes all three types of worker. In this equilibrium, a decent level of knowledge stock allows specialists to emerge. Workers with moderate ability find that it is more productive to work together as specialists, meanwhile generalists still persist since those workers in the upper tail prefer to innovate independently. Last, a specialist equilibrium is when all skilled workers are specialists and the full division of labor is achieved.

Using this framework, this paper argues that workers' purposive and profit-seeking investments in education play a vital role in economic growth through technological progress and demonstrates how the composition of human capital, not the level, affects the long-run growth under different stages of economic development. For instance, consider an economy with a limited knowledge stock and a relatively lagging technology level where growth is driven by technological imitation instead of innovation (Di Maria and Stryszowski, 2009). In this case, workers with average ability might choose not to receive education because the low returns to education cannot justify the fixed cost in schooling. Furthermore, workers with higher ability would be prone to become generalists rather than specialists due to the fact that technological imitation activities only need broader knowledge to copy and adapt available technology instead of specialization in a certain field to innovate, and the shallow knowledge stock as well as the lagging technology level make it costly in searching for other specialists in complementary fields. These together shape the composition of human capital which under this scenario consists of two types of workers, unskilled workers and generalists. The model also illustrates that in this generalist equilibrium

[3] See Rostow (1960).

the growth-enhancing effect of human capital composition depends on the fraction of generalists in the labor force.

This paper also helps to explain the conflicting results of many empirical works on the correlation between human capital and economic growth. Most of them use the average years of schooling as a proxy for education attainment. This methodology implicitly assumes that each year of schooling is identical and workers in different education categories are equally productive (Mulligan and Sala-i-Martin, 2000). However, the model indicates that the growth rate of output varies with the fractions of generalists and specialists in different equilibria. Without accounting for the heterogeneity in education, the effect of human capital on growth could be veiled.

1.1 Related Literature

A closely related paper to this model is Vandenbussche et al. (2006) which develops a model where technological change is the result of a combination of innovation and imitation. Both innovation and imitation use unskilled labor and skilled labor. They show that contribution of human capital to productivity growth is mainly from skilled human capital rather than total human capital. Building upon Vandenbussche et al. (2006)'s work, Di Maria and Stryszowski (2009) study the composition of human capital and economic development under a framework with migration. They show that the distortion caused by migration hinders the accumulation of appropriate skills thus it slows down economic development. Krueger and Kumar (2004) develop a model of technology adoption and economic growth in which workers can either obtain general education or vocational education. They demonstrate that general educated workers are more adaptable in operating new production technologies and the equilibrium growth rate is weakly lower in an economy that allocates more of a given amount of resources toward vocational education. Following their model, they suggest that during the 1980s and 1990s when new technologies emerged at a more rapid pace, the gap between US and Europe growth can be partly explained by different educational policies adopted, hence different human capital compositions. The model in this paper is different from Krueger and Kumar (2004), Vandenbussche et al. (2006) and Di Maria and Stryszowski (2009) in an underlying assumption that different types of skilled workers, generalist and specialist here, are not homogenous. By assigning separate skill acquiring function to generalist and specialist, it enables us to see how an individual skilled worker makes decision and becomes as a part of the human capital. One of the key features of this paper is to pinpoint the source of multiple equilibria in human capital composition by specialization in education.

This paper is also related to work on endogenous technological growth, including Lucas (1988), Romer (1986, 1990), Barro (1991), Mankiw et al. (1992) and Hall and Jones (1999), who provide insights on how endogenizing technological improvements affect economic development and emphasize the accumulation of human capital as the engine of growth.

On the other hand, a number of empirical works also suggest that different compositions of human capital on growth vary with fundamental economic factors. In particular, Durlauf and Johnson (1995) use regression tree method to find that countries with different growth rates have different human capital shares. Both Colombo and Grillis (2005) and Tsai, Hung and Harriott (2010) investigate human capital on growth by categorizing the labor force in different fields. They find human capital in scientific-technological field the most growth enhancing.

The rest of the paper is organized as follows. Section 2 introduces the model, characterizes the composition of human capital and examines the factors affecting human capital structure. Section 3 shows the composition effect of human capital on economic growth under different equilibria. Section 4 concludes and discusses policy implications and caveats.

2 The Model

In this section, I introduce an economy where workers make decisions in education and then work in different types to earn income. There are three types of workers in the economy: unskilled worker, generalist and specialist. The key decision problem for the individual is what type he chooses to be. The decision is made to maximize his net income earned through production of which the productivity is affected by workers' skill levels.

2.1 Environment

Assume there is a population of size 1. Workers are born and die at the same rate so that the population is constant. A worker lives for one period and completely consumes all of his available income. Time is discrete and indexed by t.

2.1.1 Education

Before entering the workforce, an individual can decide on whether to invest in education or not. If he chooses not to invest in education, he will be an unskilled worker. If he decides to educate himself, there are two skills P and Q available to accumulate. When he receives education, he can choose the type of his education: *Generalist* education (learning two skills, both P and Q, at the same time) or *Specialist* education (specializing in one skill, either P or Q, but having deeper understanding than non-specialist). Both generalists and specialists are skilled workers. Denote $M_t = \{M_{P,t}, M_{Q,t}\}$ as a worker's skill level set. The cost to obtain the specialist or generalist education is E.

A skilled worker's skill level is affected by his own ability and the technology level at the time he receives education, the skill level function $M_{k,t}$ for skilled workers is given by

$$M_{k,t} = X^{\beta} A_{t-1}^{\theta} \tag{2.1}$$

$$0 < \beta < 1, 0 < \theta < 1, k \in \{P, Q\}$$

where X measures the worker's innate ability and is uniformly distributed, $X \in [0, 1]$. A_{t-1} is the country's average existing technology level in the last period, $A_{t-1} \geq 1$. β is the ability discount factor which captures counter-productive noises in skill accumulation, such as distraction in the cross-learning process. Bigger β indicates lower efficiency of a worker's innate ability in transition to skill level. θ indicates the positive intertemporal technology impact on the skill level. Workers get deeper understandings in expertise and accumulate higher skill levels if θ is bigger.

$M_{k,t}$ is the common skill level function for all skilled workers. To distinguish between two types of skilled worker, generalist and specialist, we need to impose further restrictions on β and θ.

A generalist accumulates both skills. Simultaneously learning two different skills creates distraction which reduces the quality of either skill so that the actual outcome of skill level is lower than expected. For example, learning languages. When we learn a new language, we need to build a language core including memorizing the words, grammars and sounds. You want to keep the linkages among these components, one to one. But if you learn two languages at the same time, it is very likely that you will get confused by cross memorizing. Generalists get a punishment in accumulating skills because of multitasking. Therefore, we assume $\beta_G > \beta_S$ so that the ability discount factor is greater on generalists. This implies a generalist relies more on his innate ability to accumulate skill levels than a specialist do. On the other hand, a specialist focuses on one skill to obtain deeper expertise in that specific area. Higher technology level in the earlier stage provides larger knowledge stock for a specialist to delve into and also makes it harder for a generalist to comprehend both skills. Therefore, we assume $\theta_S > \theta_G$ which means specialists benefit more from previous technology stock than generalists do.

Thus, an individual makes educational decision to become one type of worker and enters the labor force with his corresponding skill level set.

Unskilled Worker If a worker chooses not to receive education, he becomes an unskilled worker and has zero skill level in either skill P or Q. So his skill level set is $M_t^U = \{0, 0\}$.

Generalist If a worker chooses to become a generalist, he would devote half of his time to each skill in order to maximize the total skill level accumulated and therefore be skillful in both P and Q skills (but not as skillful as a specialist is in one single area).[4] So a generalist's skill level set is $M_t^G = \{\frac{1}{2}M_{P,t}^G, \frac{1}{2}M_{Q,t}^G\}$. The skill level function of generalists is given by

$$M_{k,t}^G = X^{\beta_G} A_{t-1}^{\theta_G}, k \in \{P, Q\} \tag{2.2}$$

Specialist If a worker chooses to become a specialist, he would be very skillful in one skill but unskilled in the other. So a specialist's skill level set is $M_t^S = \{M_{P,t}^S, 0\}$ if he specializes in skill P or $\{0, M_{Q,t}^S\}$ if he specializes in skill Q. The skill level

[4] The rationale of investing half of his time into each skill will be explained once technology is introduced.

function of specialists is given by

$$M_{k,t}^{S} = X^{\beta_S} A_{t-1}^{\theta_S}, k \in \{P, Q\} \tag{2.3}$$

2.1.2 Coordination

An unskilled worker without education immediately starts to work after he is born. Unskilled workers are identical and perfectly substitutable. Skilled workers can improve technology by pairing P and Q skills. There is a coordination cost $\widetilde{c} \geq 0$ associated with such pairing. Bigger $\widetilde{c}$ means higher coordination cost. Since generalists learn both P and Q skills, the coordination cost is assumed to be zero for them implying that they can innovate independently. The coordination cost arises among specialists who are only expert in one skill and require other specialists in complementary fields in innovation activities. Such searching process is costly, especially in developing countries where labor market is not well organized and information accessibility is limited.[5]

For the purpose of simplicity in exposition, we define $c \equiv 1 + \widetilde{c}$ so that $c \geq 1$ and $c = 1$ implies zero coordination cost for generalists.

2.1.3 Technological Progress

In this model, the technology is endogenously driven by skilled workers who are able to improve their expertise and innovate or get access to a better technology. To explain how they improve the technology level, I specify the technological innovation function as the following.

[5]We do not consider pairing a specialist with a generalist here because with a generalist investing only one half of his time in one complementary skill and one half in the other overlapping skill, it will decrease the pairing specialist's gain.

For a worker i,

$$A_{i,t} = A_{t-1} + c^{-1}(M_{P,t}^{\alpha} + M_{Q,t}^{\alpha})^{\frac{1}{\alpha}},\ \alpha < 0 \tag{2.4}$$

where $M_{P,t}$ and $M_{Q,t}$ are the skill levels of two skills P and Q respectively. c is the coordination cost. A_{t-1} is the average existing technology level that $A_{t-1} = \int_0^1 A_{i,t-1} dX_i$.[6] $1/(1-\alpha)$ is the elasticity of substitution. Since $\alpha < 0$, we have $1/(1-\alpha) < 1$, this ensures that these two skills are complementary in the advancement of technology.

The technology level in current period depends on the existing technology level in last period, a combination of skill levels in P and Q and coordination cost. It is easy to see current technology level is positively related to skill levels and negatively related to coordination cost.

Since we have three types of worker, the technological innovation function is different for each type.

Unskilled Worker An unskilled worker does not receive education so that he has zero skill levels in either P or Q, i.e. $M_{P,t} = M_{Q,t} = 0$.
Therefore

$$A_{i,t}^{U} = A_{t-1} \tag{2.5}$$

This implies unskilled workers do not contribute anything to technological progress but they still can use better technology over time if the existing technology level A_{t-1} grows either from external intrusion or endogenous innovation.

[6]Since each worker, according to his innate ability $X_i \sim U[0,1]$, possesses a different kind of technology to use in producing intermediate goods, the total technology level is the aggregation of all varieties of technology that is given by $\int_0^1 A_{i,t-1} dX_i$. Recall that the population size is 1 which implies the average existing technology $A_{t-1} = \int_0^1 A_{i,t-1} dX_i$. A_{t-1} is endowed exogenously to each worker in the next period.

Generalist If the worker receives generalist education, the best he can do is to split his time equally doing P and Q. Coupled with skill level function of generalist (2), the technology innovation function of generalists is given by

$$A_{i,t}^G = A_{t-1} + c^{-1}\left((\frac{1}{2}X^{\beta_G}A_{t-1}^{\theta_G})^\alpha + (\frac{1}{2}X^{\beta_G}A_{t-1}^{\theta_G})^\alpha \right)^{\frac{1}{\alpha}}$$
$$= A_{t-1} + 2^{\frac{1-\alpha}{\alpha}}X^{\beta_G}A_{t-1}^{\theta_G} \tag{2.6}$$

Note generalists devote half of his time to each skill in order to maximize the integrated skill level[7]. Also recall that since generalists innovate independently, the coordination cost $c = 1$ which means there is no coordination loss in innovation.

Specialist Specialists need pairing to cooperate with each other (i.e. share their skill level sets) in technology innovation. Therefore, we assume that if a worker receives specialist education in skill P, he will team up with another specialist with similar ability (same X) who is an expert in skill Q.[8] Together with equation (3), the

[7]To maximize the integrated skill level, it's equivalent to

$$\max_\tau \, (\tau X^{\beta_G}A_{t-1}^{\theta_G})^\alpha + \left((1-\tau)X^{\beta_G}A_{t-1}^{\theta_G}\right)^\alpha$$

First order conditions give $\alpha X^{\beta_G}A_{t-1}^{\theta_G}(\tau X^{\beta_G}A_{t-1}^{\theta_G})^{\alpha-1} = \alpha X^{\beta_G}A_{t-1}^{\theta_G}\left[(1-\tau)X^{\beta_G}A_{t-1}^{\theta_G}\right]^{\alpha-1}$. Thus, the optimal $\tau = \frac{1}{2}$.

[8]We assume a specialist can always find another specialist in complementary skill with similar ability level, i.e. Positive Assortative Matching (PAM). To have PAM, a sufficient and necessary condition is supermodularity. See Eeckhout and Kircher (2010).

Since $A_{i,t}^S = A_{t-1} + c^{-1}\left((X_P^{\beta_S}A_{t-1}^{\theta_S})^\alpha + (X_Q^{\beta_S}A_{t-1}^{\theta_S})^\alpha\right)^{\frac{1}{\alpha}}$,

$$\frac{\partial^2 A_{i,t}^S}{\partial X_P \partial X_Q} = c^{-1}\beta_S^2(1-\alpha)\left((X_P^{\beta_S}A_{t-1}^{\theta_S})^\alpha + (X_Q^{\beta_S}A_{t-1}^{\theta_S})^\alpha\right)^{\frac{1}{\alpha}-2}(X_P X_Q)^{\alpha\beta_S - 1}A_{t-1}^{2\alpha\theta_S}$$

Supermodularity requires $\frac{\partial^2 A_{i,t}^S}{\partial X_P \partial X_Q} > 0$ which implies $\alpha < 1$. This is indeed satisfied by the complementarity of skills condition imposed before that $\alpha < 0$. In fact, there is an equivalence between supermodularity and a standard notion of complementarity, increasing differences. Despite the cardinal property of supermodularity and the ordinal property of complementarity, complementarity implies supermodularity. See Topkis (1998) *Supermodularity and Complementarity*, Chapter 2. Supermodularity ensures Positive Assortative Matching that specialist possessing high ability in skill technology innovation function of specialists is given by

$$\begin{aligned} A^S_{i,t} &= A_{t-1} + c^{-1}\left((X^{\beta_S}A^{\theta_S}_{t-1})^{\alpha} + (X^{\beta_S}A^{\theta_S}_{t-1})^{\alpha}\right)^{\frac{1}{\alpha}} \\ &= A_{t-1} + 2^{\frac{1}{\alpha}}c^{-1}X^{\beta_S}A^{\theta_S}_{t-1} \end{aligned} \tag{2.7}$$

Inspecting equation (7), we observe that the contribution on technological progress made by the specialists depends more on the technology stock A_{t-1} and less on their own ability level X than that made by the generalists does.

2.1.4 Production

There is only one final product Y and the market of Y is perfectly competitive. Final product is produced from intermediate goods g_i produced by workers. Each worker produces one variety of intermediate goods so that the market of each intermediate good is monopolistic. Workers earn income through the sales of intermediate goods. As in Vandenbussche et al. (2006), the production function is given by

$$Y_t = \int_0^1 A^{1-\rho}_{i,t} g^{\rho}_{i,t} dX_i, \rho \in (0, 1) \tag{2.8}$$

where $A_{i,t}$ is the technology coefficient adopted by ith worker in producing intermediate good at time t, $A_{i,t} \geq 1$ and $g_{i,t}$ is the unit of intermediate good used in final good production at time t.

2.1.5 Cost and Price

Assume one unit of intermediate goods needs one unit of final good as input and we normalize the price of final good Y to 1. Then the unit cost of producing $g_{i,t}$ is just 1.

P will match with specialist in skill Q who also possesses high ability.

Since Y's market is competitive and we use it as a numeraire, the price of intermediate good $g_{i,t}$ is its marginal product,

$$p_{i,t} = \frac{dY_t}{dg_{i,t}} = \rho A_{i,t}^{1-\rho} g_{i,t}^{\rho-1} \tag{2.9}$$

2.1.6 Income

Assume each worker chooses some quantity of intermediate good $g_{i,t}$ to produce. His net income is given by

$$I_{i,t} = p_{i,t} g_{i,t} - g_{i,t} \tag{2.10}$$

By substituting the price of $g_{i,t}$, we have

$$I_{i,t} = \rho A_{i,t}^{1-\rho} g_{i,t}^{\rho} - g_{i,t} \tag{2.11}$$

A worker's income depends on the quantity of intermediate goods produced and current technology level adopted in production.

2.2 The Worker's Problem

Each type of worker maximizes his consumption $C_{i,t}$ by picking the quantity of intermediate goods $g_{i,t}$ to produce, given the pattern of technology adoption $A_{i,t}$ and his ability X.

2.2.1 Unskilled Worker

Unskilled workers do not receive education, therefore their consumption maximization problem is

$$\max_{g_{i,t}} C_{i,t} = I_{i,t} = \rho A_{i,t}^{1-\rho} g_{i,t}^{\rho} - g_{i,t} \tag{2.12}$$

Solve for $g_{i,t}$ and substitute in $A_{i,t}^U$, we have

$$g_{i,t}^{U*} = \rho^{\frac{2}{1-\rho}} A_{i,t}^U \tag{2.13}$$

Therefore at time t, the unskilled worker's optimal consumption at the equilibrium is

$$C_{i,t}^{U*} = \delta A_{i,t}^U \tag{2.14}$$

where $\delta = (\frac{1}{\rho} - 1)\rho^{\frac{2}{1-\rho}}$. For unskilled workers, they are not innovative and they will just take the average technology level from last period A_{t-1} as given, that is $A_{i,t}^U = A_{t-1}$. So the optimal intermediate goods production for unskilled workers is

$$g_{i,t}^{U*} = \rho^{\frac{2}{1-\rho}} A_{t-1} \tag{2.15}$$

then the optimal consumption is

$$C_{i,t}^{U*} = \delta A_{t-1} \tag{2.16}$$

2.2.2 Skilled Worker

For skilled workers, they choose to improve their expertise and innovate or get access to a better technology but they need to receive education which costs E. So skilled workers' consumption maximization problem is

$$\max_{g_{i,t}} C_{i,t} = I_{i,t} - E = \rho A_{i,t}^{1-\rho} g_{i,t}^{\rho} - g_{i,t} - E \tag{2.17}$$

Similar to unskilled workers, we get the optimal quantity of intermediate goods and consumption as

$$g^*_{i,t} = \rho^{\frac{2}{1-\rho}} A_{i,t} \tag{2.18}$$

$$C^*_{i,t} = \delta A_{i,t} - E \tag{2.19}$$

Although at first glance it may look similar to the results of unskilled workers problem, they are actually very different in ways of technology adoption. Skilled workers earn skill premium through innovating and improving current technology. Furthermore, generalists and specialists distinguish themselves by different innovation patterns.

Since $A^G_{i,t} = A_{t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A^{\theta_G}_{t-1}$, the optimal quantity of intermediate goods production $g^{G*}_{i,t}$ for generalists is

$$g^{G*}_{i,t} = \rho^{\frac{2}{1-\rho}} (A_{t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A^{\theta_G}_{t-1}) \tag{2.20}$$

and the optimal consumption $C^{G*}_{i,t}$ is

$$\begin{aligned} C^{G*}_{i,t} &= \delta A^G_{i,t} - E \\ &= \delta(A_{t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A^{\theta_G}_{t-1}) - E \end{aligned} \tag{2.21}$$

As for specialists, $A^S_{i,t} = A_{t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A^{\theta_S}_{t-1}$ so the optimal quantity $g^{S*}_{i,t}$ for specialists is

$$g^{S*}_{i,t} = \rho^{\frac{2}{1-\rho}} (A_{t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A^{\theta_S}_{t-1}) \tag{2.22}$$

and the optimal consumption $C_{i,t}^{S*}$ is

$$
\begin{aligned}
C_{i,t}^{S*} &= \delta A_{i,t}^{S} - E \\
&= \delta(A_{t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{t-1}^{\theta_S}) - E
\end{aligned}
\tag{2.23}
$$

2.3 Education Decision

Each worker makes his education decision based on potential maximum consumption. By comparing potential maximum gains for three types of worker, we are able to determine the cutoff ability levels of being an unskilled worker, a generalist or a specialist so that human capital composition is revealed.

2.3.1 Unskilled Worker vs Specialist

To decide whether one will choose to become an unskilled worker or specialist worker, equate (16) to (23) we get

$$
X_{u,s}^{*} = \left(\frac{E}{2^{\frac{1}{\alpha}} c^{-1} \delta A_{t-1}^{\theta_S}} \right)^{\frac{1}{\beta_S}} \tag{2.24}
$$

This is the cutoff ability level of choosing between unskilled and specialist worker. If $X > X_{u,s}^{*}$, one will choose to receive education and become a specialist worker; if $X < X_{u,s}^{*}$, one will quit school and become an unskilled worker; if $X = X_{u,s}^{*}$, the worker is indifferent.

2.3.2 Unskilled Worker vs Generalist

To decide whether one will choose to become an unskilled worker or generalist worker, equate (16) to (21) we get

$$X^*_{u,g} = \left(\frac{E}{2^{\frac{1-\alpha}{\alpha}} \delta A_{t-1}^{\theta_G}} \right)^{\frac{1}{\beta_G}} \tag{2.25}$$

This is the cutoff ability level of choosing between unskilled and generalist worker. If $X > X^*_{u,g}$, one will choose to receive education and become a generalist worker; if $X < X^*_{u,g}$, one will quit school and become an unskilled worker; if $X = X^*_{u,g}$, the worker is indifferent.

2.3.3 Specialist vs Generalist

To decide whether one will choose specialist or generalist education, equate (21) to (23) we get

$$X^*_{g,s} = (2c^{-1} A_{t-1}^{\theta_S - \theta_G})^{\frac{1}{\beta_G - \beta_S}} \tag{2.26}$$

This is the cutoff ability level of choosing between specialist and generalist education.[9] If $X > X^*_{g,s}$, one will choose generalist education; if $X < X^*_{g,s}$, one will choose specialist education; if $X = X^*_{g,s}$, the worker is indifferent.

2.4 Equilibrium

An equilibrium for given technology A_{t-1} and distribution of individual ability X_i consists of

[9]Here, we need to impose an additional restriction that $c > 2$ to make $X^*_{g,s}$ meaningful. This additional assumption ensures at least some part of $X^*_{g,s}$ is between 0 and 1 as A_{t-1} goes from 1 to $+\infty$.

- educational policy functions $h^E(A_{t-1}, X_i) = \{0, E\}$,

- individual technology levels A_i,

- quantities of intermediate goods supply and demand $\{g_i(A_i)^{supply}, g_i(A_i)^{demand}\}$ and final product Y,

- prices p_i and unit cost c_{g_i} for intermediate goods, and final product price p_Y,

such that:

1. Given prices p_i and c_{g_i}, $g_i(A_i)^{supply}$ and educational policy functions solve the workers' problem (12) and (17).

2. The individual technology levels A_i follows the law of motion (5) - (7).

3. Given prices p_i and p_Y, $g_i(A_i)^{demand}$ maximize the firm's profit of final good production.

4. Intermediate good markets clear: $g_i(A_i)^{supply} = g_i(A_i)^{demand}$.

5. Aggregate feasibility condition is satisfied: $\int_0^1 \left(g_i(A_i)^{demand} + C_i\right) dX_i = Y$.

2.5 The Composition of Human Capital

The composition of human capital is determined by the cutoff levels of different types of worker. An equilibrium is achieved when a worker makes a decision to become a certain type that maximizes his consumption given the decisions made by other workers. No one would deviate from his choice given the ability X of each worker. Depending on the values of $X^*_{u,s}$, $X^*_{u,g}$ and $X^*_{g,s}$, there are four different equilibria.[10]

[10] Although there are 24 potential permutations of the set $\{X^*_{u,s}, X^*_{u,g}, X^*_{g,s}, 1\}$, only 8 are applicable because of subtler relationships among these variables. Since

$$X^*_{u,g} > X^*_{g,s} \Leftrightarrow 2^{\frac{\beta_G - \beta_S + \alpha\beta_S}{\alpha(\beta_G - \beta_S)}} \delta c^{\frac{\beta_G}{\beta_S - \beta_G}} A^{\frac{\beta_G\theta_S - \beta_S\theta_G}{\beta_G - \beta_S}} < E \Leftrightarrow X^*_{u,s} > X^*_{u,g}$$

Unskilled Equilibrium Suppose $X^*_{g,s} > X^*_{u,g} > X^*_{u,s} > 1$, we will have an equilibrium where every worker will choose to be an unskilled worker. We define this as Unskilled Equilibrium (UE)[11]. Figure 1 illustrates how human capital structure is formed under such equilibrium.

In UE, even the most able worker finds it worthless to invest in education. It is always sub-optimal to be a skilled worker since $C^{U*}_{i,t}$ is always bigger than $C^{G*}_{i,t}$ or $C^{S*}_{i,t}$ for any $X \in [0, 1]$. Since we assume the population size is 1 and the ability level is uniformly distributed between 0 and 1, the actual quantity of unskilled workers is just 1. The unskilled equilibrium is a case when education cost is extremely high and/or technology stock is extremely small.

---

which implies $X^*_{u,s} > X^*_{u,g} > X^*_{g,s}$ or $X^*_{g,s} > X^*_{u,g} > X^*_{u,s}$. Therefore, with the extra restrictions, we can reduce the problem into 8 cases and group them into 4 equilibria.

[11]The equilibrium also holds when $X^*_{u,s} > X^*_{u,g} > X^*_{g,s} > 1$ or $X^*_{u,s} > X^*_{u,g} > 1 > X^*_{g,s}$.

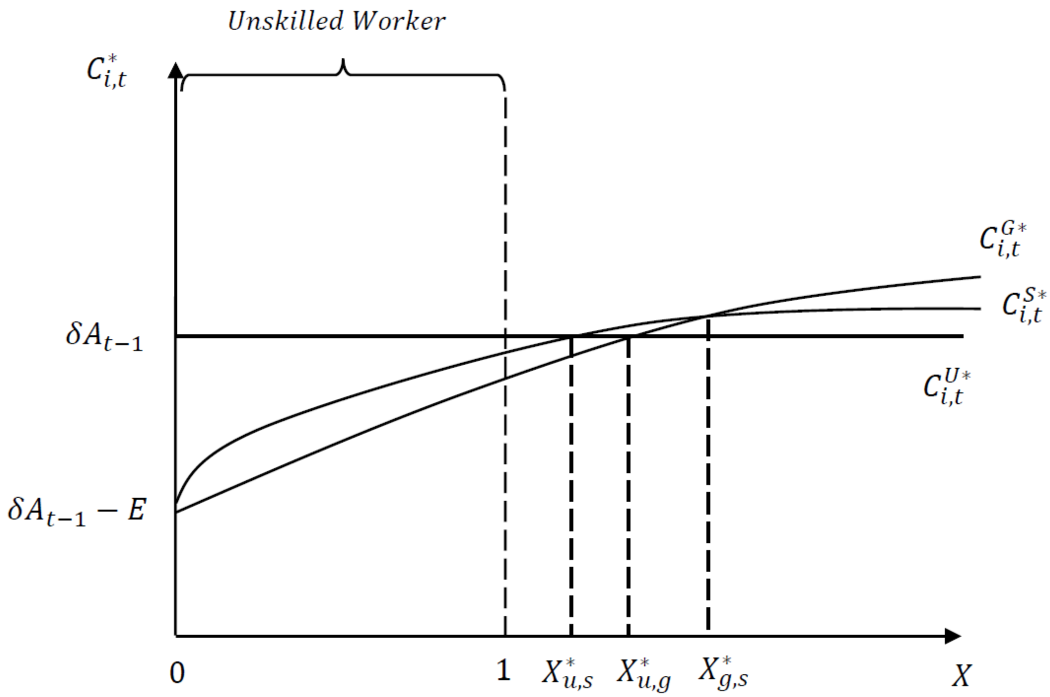

Figure 1.1: Ability Level and Human Capital Composition Under UE

Generalist Equilibrium Suppose $1 > X^*_{u,s} > X^*_{u,g} > X^*_{g,s}$, investment in education becomes profitable for some workers with higher ability. However, a worker will always choose to be a generalist if he decides to educate himself. Therefore, we call this equilibrium as Generalist Equilibrium (GE)[12]. See Figure 2 for illustration.

[12]The equilibrium also holds when $X^*_{u,s} > 1 > X^*_{u,g} > X^*_{g,s}$.

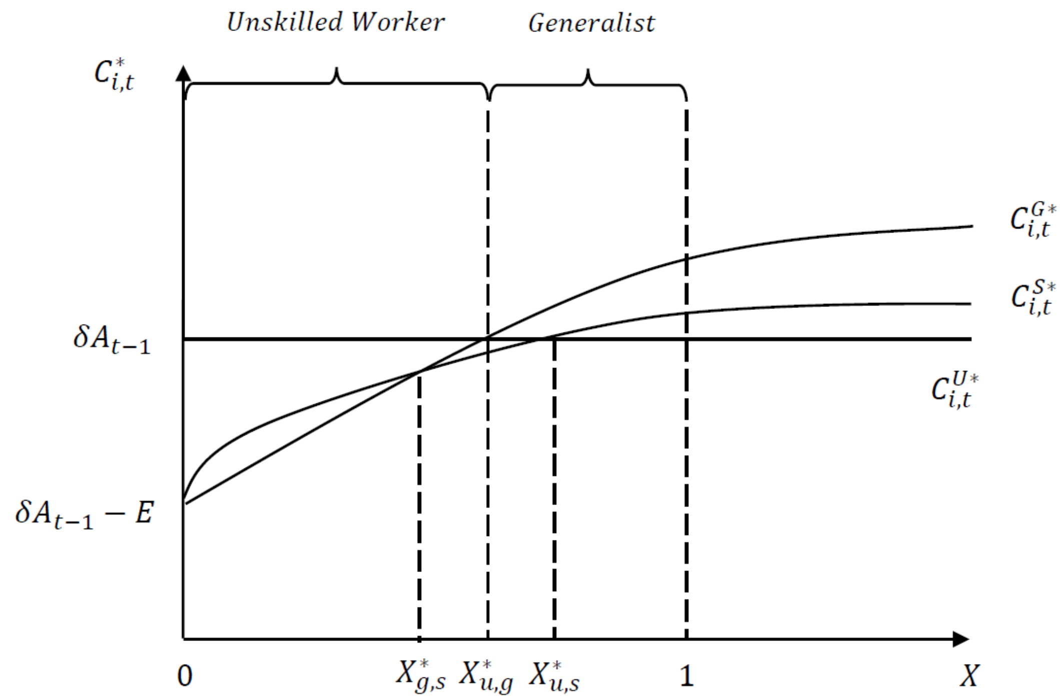

Figure 1.2: Ability Level and Human Capital Composition Under GE

In GE, skilled workers emerge as the 'threshold' is now lower so that abler workers can obtain more consumption as being educated. However, they only choose to become generalists. Even for those in the top tail of the ability spectrum (i.e. $X \in [X^*_{u,s}, 1]$) who are better off to be specialists over unskilled workers, they will still choose to be generalists because $C^{G*}_{i,t}$ dominates $C^{S*}_{i,t}$ over the interval $[X^*_{g,s}, 1]$. Therefore, the quantity of unskilled workers in GE is $X^*_{u,g}$ and the quantity of generalists is $1 - X^*_{u,g}$. GE exists where education cost is modest, technology stock is relatively small and coordination cost is very high.

Mixed Equilibrium Suppose $1 > X^*_{g,s} > X^*_{u,g} > X^*_{u,s}$, a more complicated but more intriguing equilibrium arises where all three types of worker exist contemporaneously in the economy. We define such equilibrium as Mixed Equilibrium (ME).

The equilibrium is plotted in Figure 3.

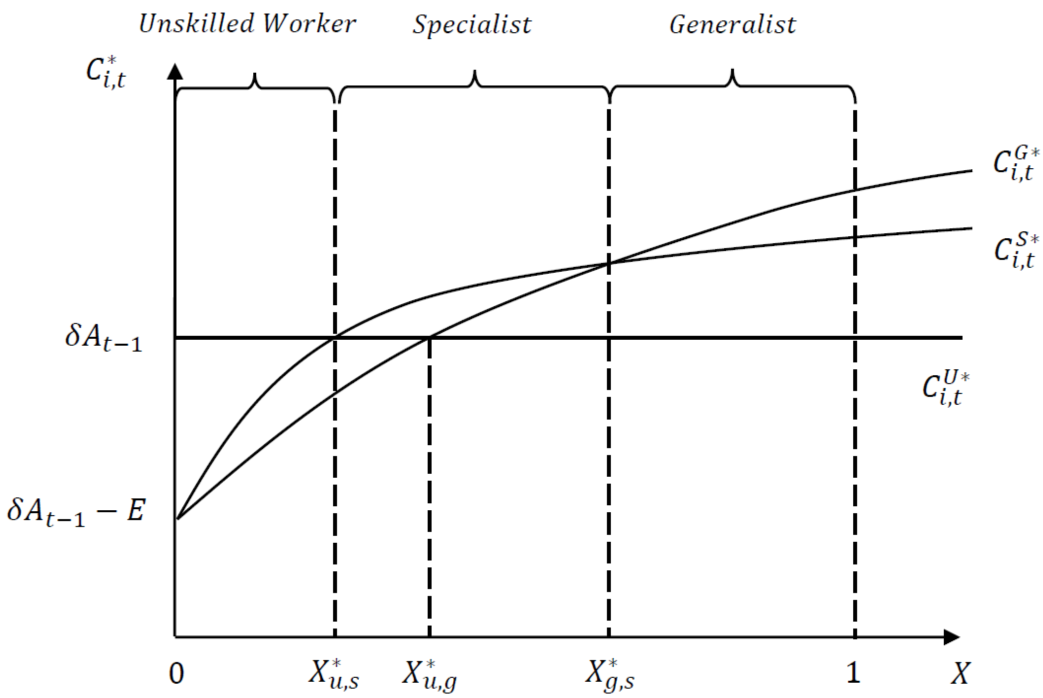

Figure 1.3: Ability Level and Human Capital Composition Under ME

In ME, one with ability level lower than $X^*_{u,s}$ will become an unskilled worker; one with ability level higher than $X^*_{u,s}$ but lower than $X^*_{g,s}$ will choose to be a specialist; one with ability level higher than $X^*_{g,s}$ will choose to be a generalist. In this equilibrium, the skilled labor force is no longer composed of one pure type of worker but a mix of two types. An abler worker deviates from being a specialist to a generalist if his ability $X > X^*_{g,s}$ because $C^{G*}_{i,t}$ dominates $C^{S*}_{i,t}$ over the interval $[X^*_{g,s}, 1]$. Therefore, the quantity of unskilled workers is $X^*_{u,s}$, and the quantity of specialists and generalists are $X^*_{g,s} - X^*_{u,s}$ and $1 - X^*_{g,s}$ respectively. ME exists in an economy with relatively low education cost, relatively large technology stock and modest coordination cost.

Specialist Equilibrium Suppose $X^*_{g,s} > 1 > X^*_{u,g} > X^*_{u,s}$, there will be an equilibrium where unskilled workers and skilled workers both exist while all of the skilled workers are specialists. We define such equilibrium as Specialist Equilibrium (SE)[13]. Figure 4 illustrates how human capital structure is formed under SE.

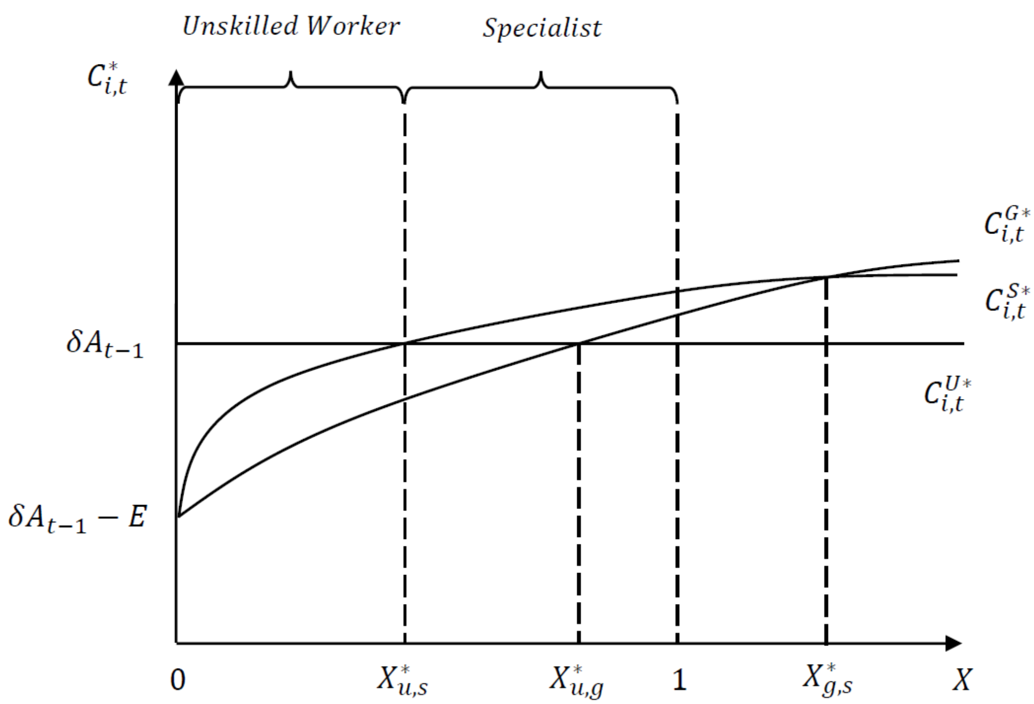

Figure 1.4: Ability Level and Human Capital Composition Under SE

In SE, it is analogous to GE that although an individual in the top tail of the ability spectrum (i.e. $X \in [X^*_{u,g}, 1]$) can choose to be a generalist over uneducated, he won't deviate from becoming a specialist since $X^*_{g,s} > 1$ which implies any worker should choose to become a specialist whenever he decides to be a skilled worker. Therefore, the quantity of unskilled worker is $X^*_{u,s}$ and the quantity of specialists is $1 - X^*_{u,s}$. SE exists in an economy with extremely low education cost and coordination cost as well as extremely large technology stock.

[13]The equilibrium also holds when $X^*_{g,s} > X^*_{u,g} > 1 > X^*_{u,s}$.

Equations (24), (25) and (26) explicitly show that the human capital composition is affected by education cost E, coordination cost c and average existing technology level A_{t-1}. Thus, a comparative statics analyzing their impacts individually provides a deeper understanding in how human capital structure is composed.

2.5.1 Effect of Average Existing Technology Level

Figure 5 shows the effect of average existing technology level A_{t-1} on human capital structure, given other factors remain constant. If the existing technology level is lower than A_1, that is $X^*_{u,s} > X^*_{u,g} > 1 > X^*_{g,s}$, since $X \in [0, 1]$, no one would choose to become a skilled worker because he cannot gain from innovation. So workers will just employ the average existing technology level into production. Thus, there will be only unskilled workers in the labor force and the economy is in UE. This is actually the problem that many less developed countries are facing, the 'poverty trap' that the economy is stagnated because of a vicious circle between small technology stock and extremely slow human capital accumulation. When A_{t-1} is higher than A_1 but lower than A_2, $1 > X^*_{u,s} > X^*_{u,g} > X^*_{g,s}$, so the economy is in GE. Some unskilled workers who have stronger abilities will choose to receive generalist education. And we can see that the cutoff level to become generalists decreases, i.e. the number of unskilled workers becoming generalists increases, as the previous average technology level increases. The quantity of unskilled worker is $X^*_{u,g}$ and that of generalists is $1 - X^*_{u,g}$. Once A_{t-1} is higher than A_2, that is $1 > X^*_{g,s} > X^*_{u,g} > X^*_{u,s}$, some workers who possess medium abilities will deviate to receive specialist education because the productivity of specialists rely more on technology stock than generalists so that specialists benefit more from increasing technology, but those who are at the top will still choose to be generalists as the extra premium as being a specialist does not provide enough incentive for them to deviate. So there will be unskilled workers, generalists and specialists in the labor force at the same time and the economy is in ME. The quantity of unskilled workers is $X^*_{u,s}$. The quantity of generalists is $1 - X^*_{g,s}$ and the quantity of specialists is $X^*_{g,s} - X^*_{u,s}$. If we have an even bigger $A_{t-1} > A_3$, the economy would develop to the specialist equilibrium where specialization would yield more gains and there won't be any generalist in the labor force. The quantity of unskilled workers is $X^*_{u,s}$ and the quantity of specialists is $1 - X^*_{u,s}$.

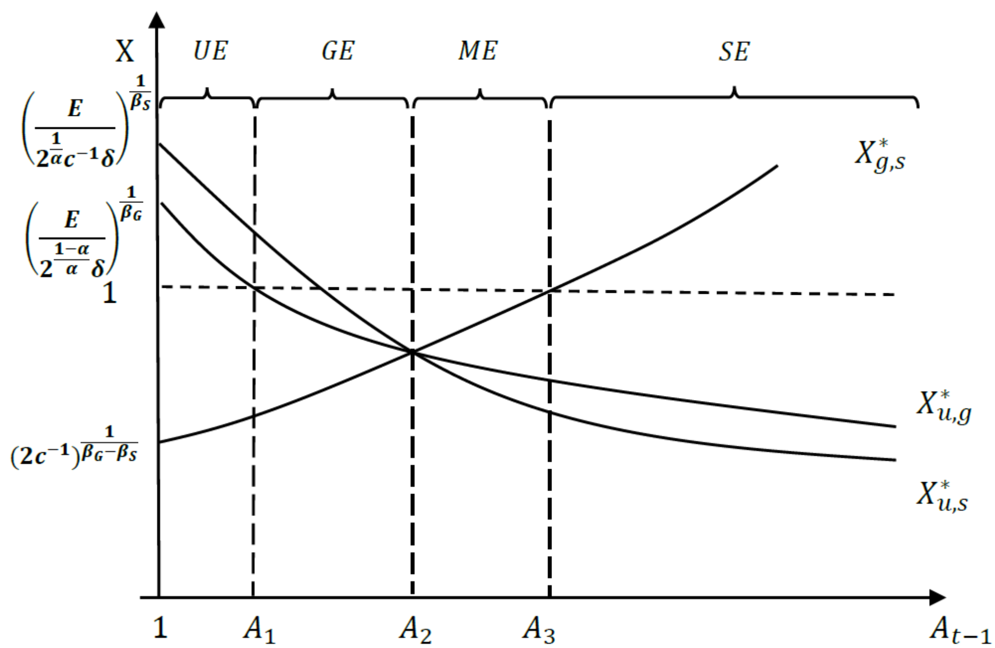

Figure 1.5: Average Existing Technology Level and Human Capital Structure

2.5.2 Effect of Coordination Cost

Coordination cost can affect the structure of skilled labor force. From equation (26), we find an inverse relationship between c and $X^*_{g,s}$. It shows us that higher coordination cost will shrink the fraction of specialists in the skilled labor force. It is more attractive to those unskilled workers to become specialists when coordination cost is small and pairing with other specialists is more efficient. From equation (24), coordination cost can also affect the fraction of unskilled workers in the whole labor force. The higher the coordination cost is, the bigger the quantity of unskilled workers is. High coordination cost decreases the gain for being a specialist. However, coordination cost has no impact on generalist education as we can see from equation (25). In other words, if there are only generalists and unskilled worker in the labor force, coordination cost will not affect the structure of human capital.

Figure 6 shows the impact of coordination cost on human capital composition. When $c < c_1$, the equilibrium is SE. The quantity of specialists is $1 - X^*_{u,s}$ and the quantity of unskilled workers is $X^*_{u,s}$. As coordination cost increases, generalists begin to emerge so the equilibrium now is ME where the quantity of unskilled workers, specialists and generalists are $X^*_{u,s}$, $X^*_{g,s} - X^*_{u,s}$, and $1 - X^*_{g,s}$, respectively. The quantity of generalists grows as c becomes larger. When $c > c_2$, GE is achieved. Since there are only generalists and unskilled workers in the economy, the ratio of unskilled workers and generalists is constant and irrelevant to the coordination cost. The quantity of generalists is $1 - X^*_{u,g}$ and the quantity of unskilled workers is $X^*_{u,g}$.

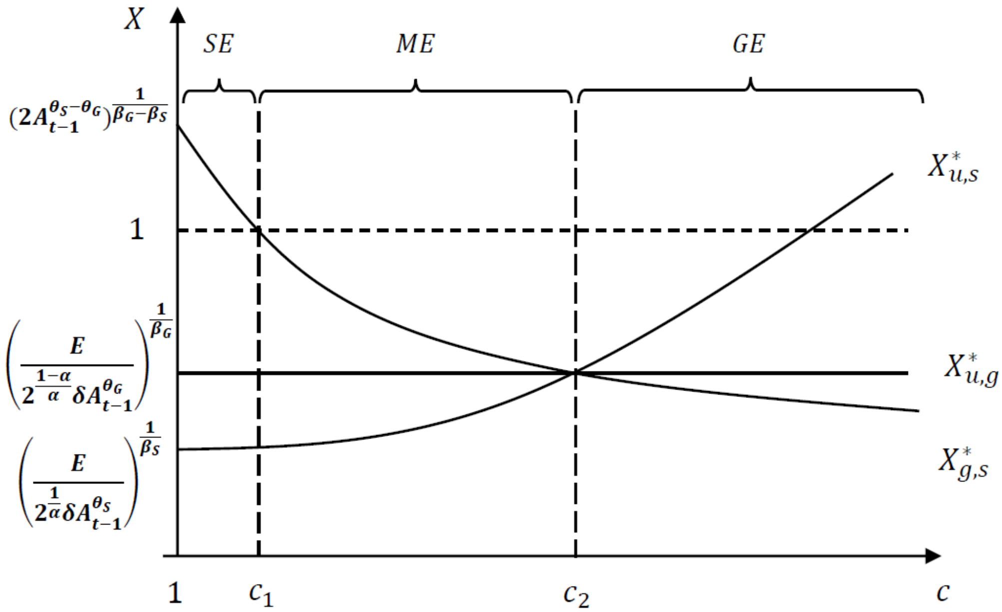

Figure 1.6: Coordination Cost and Human Capital Structure

2.5.3 Effect of Education Cost

Figure 7 shows how education cost influences the human capital structure. For example, we begin with low education cost E_1 which is in ME. The quantity of unskilled workers is $X^*_{u,s}$, the quantity of generalists is $1-X^*_{g,s}$ and the quantity of specialists is $X^*_{g,s} - X^*_{u,s}$. Relatively low education cost provides workers with more opportunities to get educated. As education cost gets higher, fewer workers are able to afford the expenses and the quantity of specialists decreases, while the quantity of unskilled workers increases. When education cost rises to E_2, there will be no specialists (GE) and the quantity of generalists begins to decrease as well. The quantity of generalists is $1 - X^*_{u,g}$ and the quantity of unskilled workers is $X^*_{u,g}$. If the cost goes up further more to E_3, all workers are unskilled (UE). There is no incentive for individuals to invest in education. More expensive education squeezes out specialists first, then after certain point the quantity of generalists begins to fall as well. On the other hand, the quantity of unskilled workers keeps growing with each increment of education cost.

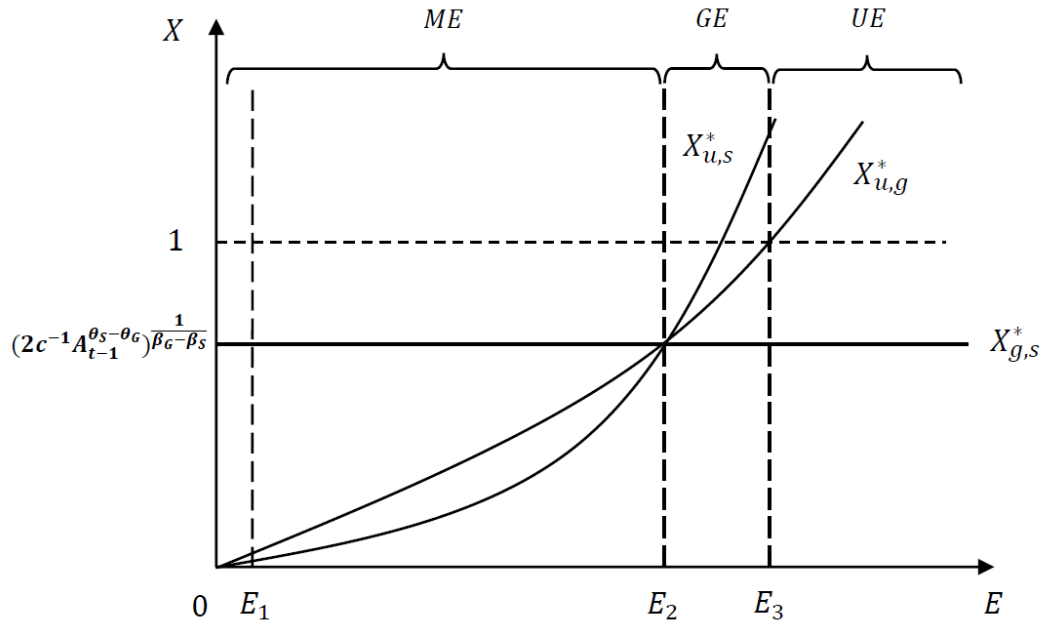

Figure 1.7: Education Cost and Human Capital Structure

In this section, I introduce a model to capture those key factors in determining the human capital composition. The core of the model is to embed the idea that education decisions made by individuals are directly linked to the composition of human capital. Individuals make decision to maximize consumption based on the assessment of technology progress, coordination cost and education cost. We conclude with three main arguments in this model:

1) The fraction of unskilled workers decreases in the labor force as average existing technology level increases in GE, ME and SE. Higher coordination cost and higher

education cost both drive more workers to become unskilled workers.

2) As average existing technology level increases, generalists' fraction in the labor force increases in GE while decreases in ME. Higher coordination cost is positively associated with the fraction of generalists in ME but has no impact on human capital structure in GE. The fraction of generalists is not sensitive to relatively small education cost increase but it does shrink when education cost escalates to a certain level.

3) There is a certain level of average existing technology for specialists to emerge. Specialists gain more fractions in the labor force as average existing technology level increases in ME and SE. Higher coordination cost and higher education cost both negatively impact specialists' fraction.

3 Human Capital Composition and Economic Growth

A significant amount of macro growth literature (Lucas, 1988; Mankiw et al, 1992; Hall and Jones, 1999) has investigated how human capital is related to a country's economic growth rate. However, it is not straightforward to explain the economic growth differences across countries by solely including the stock of human capital. Human capital develops an economy through multiple mechanics. Countries in different stages of economic development form their unique human capital structures and such heterogeneity in return can explain how different human capital compositions contribute to the growth structurally. Some literature only consider the level effect of human capital on the growth (Mincer, 1974). In this section, my aim is to focus on the composition effect of human capital on the economic growth under different equilibria.

We start by defining the growth rate of technology $r_{A,t}$ at time t which is given by

$$r_{A,t} = \frac{A_t - A_{t-1}}{A_{t-1}} \tag{3.27}$$

Since the production function is linearly related to technology at the equilibrium, the growth rate of output is the same as the growth rate of technology.[14]

We have explored four different equilibria of human capital structure, therefore it is necessary to examine the composition effect case by case.

3.1 Unskilled Equilibrium

In unskilled equilibrium, all workers are unskilled and uneducated. They just take average technology level from last period which implies there is no growth of technology in UE that is

$$A_t^{ue} = \int_0^1 A_{i,t}^U dX_i = A_{t-1} \tag{3.28}$$

and the growth rate at the equilibrium is given by

$$r_{A,t}^{ue*} = \frac{A_t^{ue} - A_{t-1}}{A_{t-1}} = \frac{A_{t-1} - A_{t-1}}{A_{t-1}} = 0 \tag{3.29}$$

If we plot the growth rate $r_{A,t}^{ue}$ against time in UE, it will be an overlapping line on the horizontal axis as shown in Figure 8.

[14] At the equilibrium, we have $g_{i,t}^* = \rho^{\frac{2}{1-\rho}} A_{i,t}$ so that $Y_t^* = \int_0^1 A_{i,t}^{1-\rho} g_{i,t}^{*\rho} dX_i = \int_0^1 \rho^{\frac{2\rho}{1-\rho}} A_{i,t} dX_i = \rho^{\frac{2\rho}{1-\rho}} A_t$. The growth rate of output is $r_{Y,t} = \frac{Y_t^* - Y_{t-1}^*}{Y_{t-1}^*} = \frac{A_t - A_{t-1}}{A_{t-1}} = r_{A,t}$.

Figure 1.8: Growth Rate Over Time in UE

Thus, the economy under UE is stagnant with zero growth rate in technology. This is the case when technology level is below A_1 in figure 5 which is exactly how the poverty trap deters a country's economic development when there is not enough incentive for workers to take education and innovate to improve technology. For those less developed countries, jumping out of the lower bound of technology from participation in globalization and imports containing high-tech is the key to avoid the stagnancy and obtain economic growth.

3.2 Generalist Equilibrium

Once the economy develops to a certain level, workers with high ability will choose to be generalists and the rest will be unskilled. So the technology growth will be driven by the innovation of generalists which is given by

$$\begin{aligned} A_t^{ge} &= \int_0^{X_{u,g}} A_{i,t}^U dX_i + \int_{X_{u,g}}^1 A_{i,t}^G dX_i \\ &= A_{t-1} + \frac{2^{\frac{1-\alpha}{\alpha}} A_{t-1}^{\theta_G}}{1+\beta_G}(1 - X_{u,g}^{1+\beta_G}) \end{aligned} \tag{3.30}$$

and the growth rate of technology at the equilibrium is

$$\begin{aligned} r_{A,t}^{ge*} &= \frac{A_t^{ge} - A_{t-1}}{A_{t-1}} \\ &= \frac{2^{\frac{1-\alpha}{\alpha}} A_{t-1}^{\theta_G - 1}}{1+\beta_G}(1 - X_{u,g}^{*1+\beta_G}) \end{aligned} \tag{3.31}$$

It is easy to see that $\frac{\partial r_{A,t}^{ge*}}{\partial X_{u,g}^*} < 0$ which implies a negative relationship between the growth rate of technology and the quantity of unskilled workers. In other words, the more generalists in the economy the faster the technology grows in GE. A further corollary would be that an educational subsidy is both consumption and growth enhancing.[15] The intuition behind this is straightforward that with lower educational cost, the existing generalists get more to consume. Furthermore, it encourages potential unskilled workers to receive education and become generalists even for those who possess lower ability levels. The marginal increase in the fraction of generalists also contributes to the total consumption. Increasing the fraction of generalists, who are more productive and innovative than unskilled workers, is equivalent to obtaining higher growth rate in GE.

Figure 9 shows the growth rate over time in GE. As technology level grows over time, the growth rate increases at an increasing pace first then at an decreasing pace. This finding coincides with the result in some technology frontier literature which

[15] See Appendix A.1 for the proof.

suggests that countries with lagging technology reaches the steady state as they converge to the technology frontier.[16] As long as the economy remains under GE, it keeps incentivizing more workers to become generalists and approaching to the local technology frontier (i.e. A_2) in GE. Having more generalists fosters the growth of the economy while the closing technological gap vanishes the additional generalists' marginal contributions to the growth rate. The generalists' positive marginal effect on the growth rate is greater than the negative closing gap effect when the existing technology is much lower than the local frontier. However, this catching-up effect is reduced as the technological gap disappears.

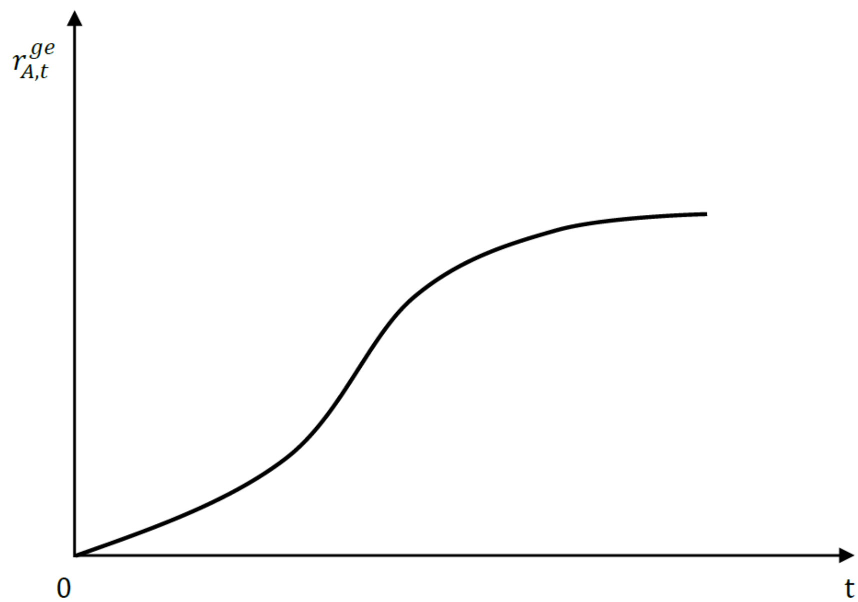

Figure 1.9: Growth Rate Over Time in GE

[16] See Di Maria and Stryszowski (2009)

3.3 Mixed Equilibrium

If the economy continues to grow, specialists will begin to emerge and we will reach to the most intriguing scenario–mixed equilibrium–where unskilled workers, generalists and specialists exist contemporaneously. In this case, the technological progress is driven by both generalists and specialists so that

$$\begin{aligned} A_t^{me} &= \int_0^{X_{u,s}} A_{i,t}^U dX_i + \int_{X_{u,s}}^{X_{g,s}} A_{i,t}^S dX_i + \int_{X_{g,s}}^1 A_{i,t}^G dX_i \\ &= A_{t-1} + \frac{2^{\frac{1}{\alpha}} c^{-1} A_{t-1}^{\theta_S}}{1+\beta_S}(X_{g,s}^{1+\beta_S} - X_{u,s}^{1+\beta_S}) + \frac{2^{\frac{1-\alpha}{\alpha}} A_{t-1}^{\theta_G}}{1+\beta_G}(1 - X_{g,s}^{1+\beta_G}) \end{aligned} \tag{3.32}$$

and the growth rate at the equilibrium is

$$\begin{aligned} r_{A,t}^{me*} &= \frac{A_t^{me} - A_{t-1}}{A_{t-1}} \\ &= \frac{2^{\frac{1}{\alpha}} c^{-1} A_{t-1}^{\theta_S - 1}}{1+\beta_S}(X_{g,s}^{*1+\beta_S} - X_{u,s}^{*1+\beta_S}) + \frac{2^{\frac{1-\alpha}{\alpha}} A_{t-1}^{\theta_G - 1}}{1+\beta_G}(1 - X_{g,s}^{*1+\beta_G}) \end{aligned} \tag{3.33}$$

If we examine (33) closely, the former item on the right hand side actually represents the effect of specialists on growth rate and the latter shows the effect of generalists. The effect of specialists expands while the effect of generalists shrinks in ME since $X_{g,s}^*$ increases and $X_{u,s}^*$ decreases over time. We conclude from the following argument that the growth rate in ME is also increasing. The reason is three-fold: (i) As technology grows, the remaining part of existing generalists can innovate more efficiently so that their contributions to the technological progress are higher. Consider journalism as an example. The size of this industry has been shrinking constantly in last two decades. However, with the aid of modern technology such as laptops and mobile apps, a journalist can access everything they need without staying in the office with a typewriter. (ii) The transforming part of existing generalists who become specialists is more productive as they change the way how they innovate. This implicitly links to the advantage of Smith's division of labor. (iii) More unskilled workers choose to become specialists as higher payoffs associated with more advanced technology justify the educational cost so that the fraction of skilled workers increases. For instance, during the information age of the 1980s and 1990s in U.S., the rapid technological changes led to a sharp increase from 53% to 78% in tertiary education enrollment to meet the skill shortages. Therefore, with increasing fraction of specialists and decreasing fraction of generalists, the growth rate in ME increases.

Furthermore, reducing coordination cost and/or educational cost has positive effect on the total consumption as well as the growth rate.[17] The economic rationale behind this is straightforward. The deduction in the coordination cost affects the human capital structure and the growth rate in two ways. On one hand, it attracts some unskilled workers to become specialists so that there are more workers involving in technological progress. On the other hand, it makes specialists more productive than generalists, at least for those who are at the bottom tier of the generalists, so some of them switch into specialists to earn higher income and innovate more efficiently. Combining these two effects, increasing fraction of specialists induced by lower coordination cost enhances the growth rate in ME. While reducing educational cost also increases growth rate, it is different from the two-way effect of the reduction in coordination cost. Decreasing education cost won't attract generalists to switch because the education cost is homogeneous to both specialists and generalists. Thus, decreasing education cost only increases the fraction of specialists and shrink the fraction of unskilled workers in the equilibrium but it is still growth-enhancing. Therefore, coordination cost and educational cost should serve as tools to adjust the composition of human capital should it be deviated from the equilibrium.

[17]See Appendix A.2 for the proof.

Figure 10 illustrates the growth rate over time in the mixed equilibrium. As the economy grows further to the local frontier A_3, the fraction of generalists declines and the fraction of specialists increases because innovating independently becomes less and less attractive while it is more advantageous to cooperate in technology innovation. The technology growth rate increases at a diminishing rate since the catching-up effect vanishes when the productivity premium of innovation is declining.

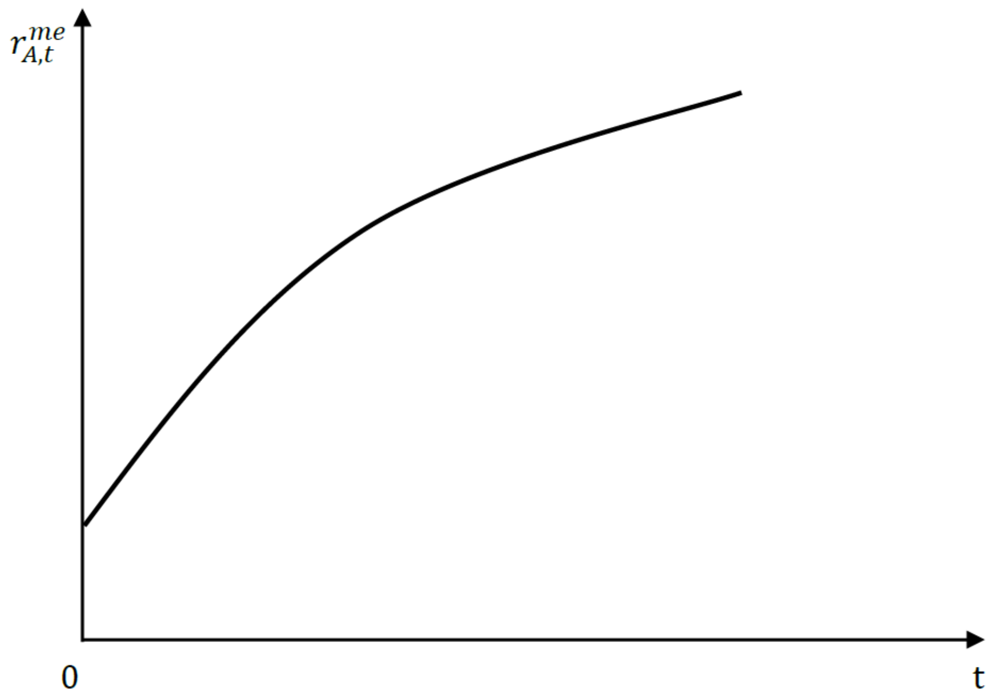

Figure 1.10: Growth Rate Over Time in ME

3.4 Specialist Equilibrium

When the technology grows further more and we reach to the level above A_3 in figure 2, all generalists switch to be specialists in this specialist equilibrium. So the technology growth is driven by specialists that

$$\begin{aligned} A_t^{se} &= \int_0^{X_{u,s}} A_{i,t}^U dX_i + \int_{X_{u,s}}^1 A_{i,t}^S dX_i \\ &= A_{t-1} + \frac{2^{\frac{1}{\alpha}} c^{-1} A_{t-1}^{\theta_S}}{1+\beta_S}(1 - X_{u,s}^{1+\beta_S}) \end{aligned} \tag{3.34}$$

and the growth rate of technology is

$$\begin{aligned} r_{A,t}^{se*} &= \frac{A_t^{se} - A_{t-1}}{A_{t-1}} \\ &= \frac{2^{\frac{1}{\alpha}} c^{-1} A_{t-1}^{\theta_S - 1}}{1+\beta_S}(1 - X_{u,s}^{*1+\beta_S}) \end{aligned} \tag{3.35}$$

Therefore, $\frac{\partial r_{A,t}^{se*}}{\partial X_{u,s}^*} < 0$ implies the more specialists the higher growth rate we have.

Similar to the corollary in GE, we can also show that $\frac{dr_{A,t}^{me*}}{dE} < 0$ and $\frac{dr_{A,t}^{me*}}{dc^{-1}} > 0$. Lower education cost and coordination cost attract more unskilled workers to become specialists so that the technology growth rate is enhanced by the increase of specialists' percentage in the economy.

The growth rate keeps rising to a certain point then begins to decline in Figure 11. Consider that the economy has achieved full specialization. There is no way to further promote the growth rate while the technology level keeps growing, making it harder and harder for the current pattern of innovation to keep up with the growth rate. The result shows that the economy approaches to its steady state in the limit which implies the convergence in economic growth.

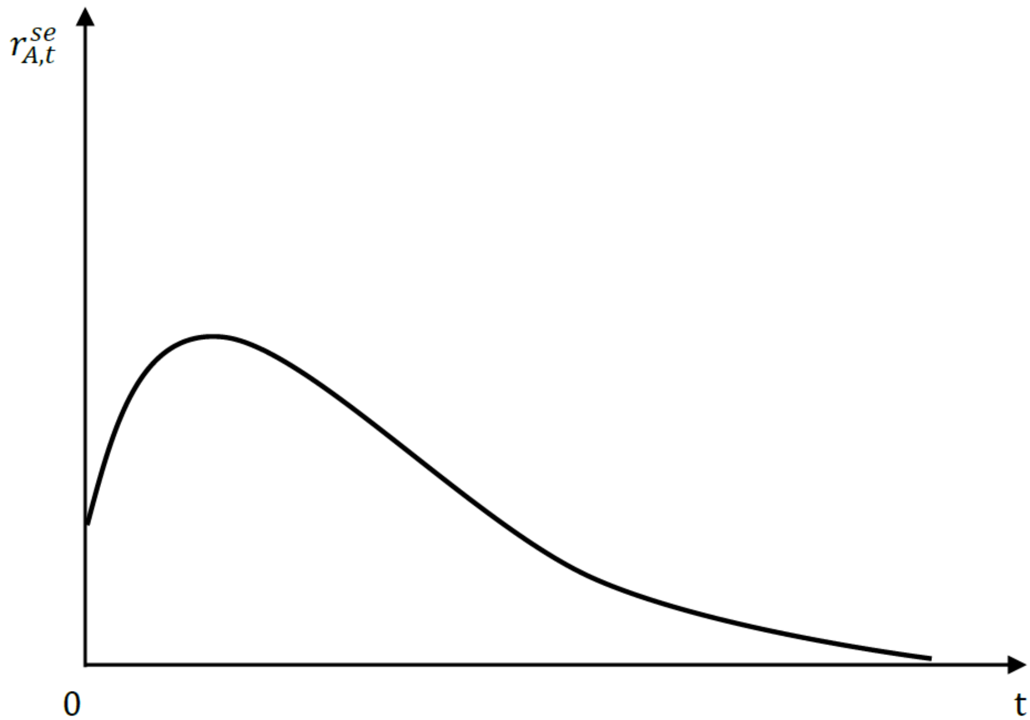

Figure 1.11: Growth Rate Over Time in SE

To wrap up this section, it might be useful to inspect the economy's growth over the spectrum of these four equilibria. Figure 12 illustrates the growth rate under different equilibria and Figure 13 shows the corresponding logarithmic technology level over time.[18]

[18]See Appendix A.3 for further details.

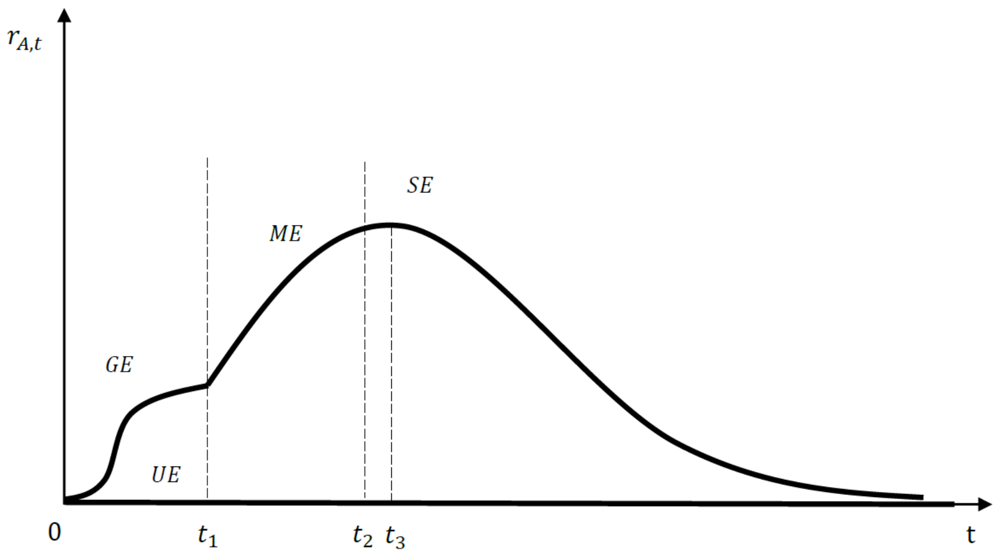

Figure 1.12: Growth Rate Over Time

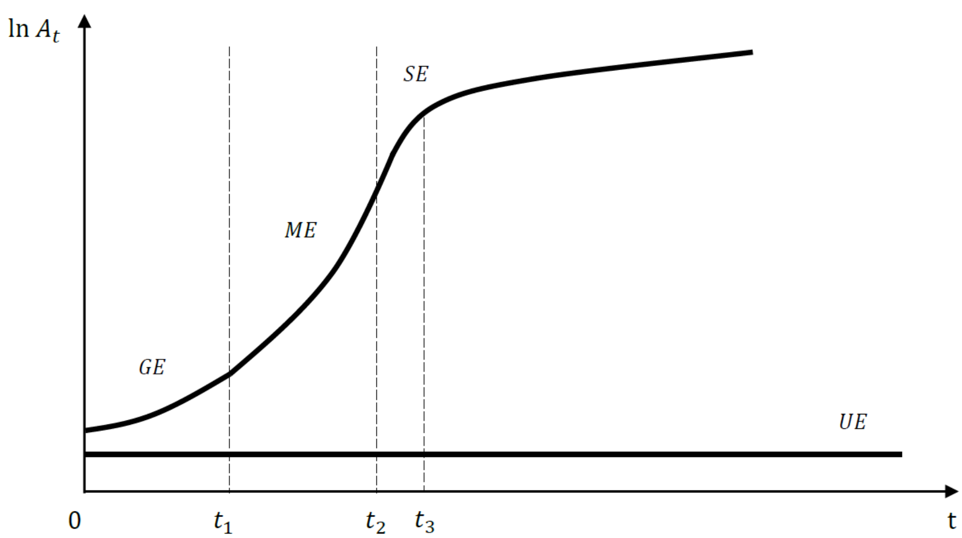

Figure 1.13: Logarithmic Technology Level Over Time

The first and foremost is that increasing the fraction of skilled workers is always growth enhancing before the peak where $t = t_3$. After the peak, the growth rate begins to fall and technology level grows at a decreasing pace. Our analysis shows that when an economy is under UE with very low technology stock, it will face a development trap where both total consumption and growth rate are stagnant. To jump out of this vicious circle, a positive technology shock is necessary. Many African and Arab nations who are considered as least developed countries are clear examples that most of their national income rely on unskilled industries such as agriculture, forestry and fishing. Extremely large fraction of unskilled workers and low industrialization put these economies into a lagging economic development. To avoid the stagnation, some economies resort to integrate into global markets so imitation of advanced technology and improved production becomes accessible. In this economic stage, the range of technology spreads and existed technologies advance. Information explosion accelerates the expansion of production and stimulates the need for better education. Generalists emerge as the time requires to absorb the massive kinds of imitated technology. The technology level and the economy start to climb in GE at an increasing rate as the fraction of generalists rises in the labor force. After the take-off, the economy continues to experience the rapid process of urbanization and industrialization. The need for specialists arises as we seek technological breakthrough to foster the economic growth so the economy enters into ME. Workers in ME start to acquire greater skills and the economy's technology advancement shifts from imitation of foreign imports to domestic innovation. The economy drives to maturity as specialization occurs during the period. As the economy grows further to SE where all skilled workers are specialists, the growth rate increases at first then gradually declines. The economic intuition behind this is that with growing fraction of specialists, the advancement of technology is less frictional and the whole society is operated with greater professionalism and efficiency so that the growth rate increases. However, as the specialization deepens over time, the room for improvement is shrinking. A prime example of a country in this equilibrium is the United States. The United States constitutes a quarter of the world's GDP and has been a leader in technological innovation since the late 19th century while its growth rate has been decreasing over the past decades, from 4 percent in 50's and 60's to 3 percent in 70's and 80's to below 2 percent in the last ten years. It would not be surprising to see the United States' economy with a close to zero growth rate and a highly specialized workforce in the future following our analysis. Some researchers also argue from the perspective of natural limits restricting the expansionary trajectory of economy but this is beyond the discussion of our paper.

4 Conclusion

This paper has developed a model featuring a heterogeneous human capital structure, endogenous technological progress and educational decision, to show how human capital composition is determined and assess its effect on economic growth in different equilibria. This model provides a possible explanation for growth divergence in countries of similar technology and human capital stocks that the composition of human capital plays a vital role in economic growth, not just the level of human capital per se.

In this model, the advance of technological innovation drives the development of the economy and individuals choose to become skilled or unskilled workers according to his own ability as well as the economic stage of current economy. An economy with relatively lower technology stock will force workers to drop off school and result in a development trap with zero growth potential. To get out of such a vicious circle, the government should provide incentives, such as subsidy to education, to attract individuals to invest in education. In order to achieve a high and stable growth rate, finding the optimal composition of human capital is the key. Distortion in economic development can partially be corrected through adjusting the composition of human capital. However, as the adjustment reaches to its ceiling, the growth-enhancing composition effect tapers off and the government ought to shift its focus onto other aspects, such as demographic dividend and global trade participation, to increase the economic growth potential.

CHAPTER 2

MIGRATION EFFECTS ON HOME COUNTRY'S COMPOSITION OF HUMAN CAPITAL AND ECONOMIC DEVELOPMENT

1 Introduction

As the world experiences rapid technological advancement and becomes a more integrated economy, the population of international migration has increased enormously over the past five decades.[1] Migration emerges as a new channel through which a country's human capital structure and economic growth are influenced.[2] Intuitively, a brain drain due to the migration of workers with high levels of human capital is considered to be detrimental to the home country which has invested significant amount of educational material and time in training those skilled workers (Bhagwati and Hamada, 1974). This paper shows that, besides a negative brain drain effect, migration prospect provides incentives for educational investments and promotes domestic technological progress through the adjustment of human capital

[1] According to United Nations' International Migration Report 2015, the number of migrants has reached 244 million (3.3% of total population) in 2015, up from 173 million (2.8% of total population) in 2000 and 84 million (2.3% of total population) in 1970. High income countries host the majority of the recent growing population of international migrants. As of 2015, 71 percent of all international migrants resided in high income countries.

[2] Some countries have experienced large outflows of skilled workers but achieved high economic growth. For example, in 1990, South Korea, Sri Lanka and Singapore had skilled emigration rates of about 9%, 30%, 25%, respectively. However, they grew much faster than those countries with smaller outflows of skilled workers, such as India (3.9%) and Bangladesh (2.1%).

composition so that countries with relatively low ex ante fraction of skilled workers can actually obtain higher economic growth rates from such human capital flight.

The aim of this paper is to theoretically analyze the effects of migration on home country's economic development with endogenous technological progress, educational decisions and composition of human capital. Talented people tend to migrate in general from poor countries to rich ones because of a higher standard of living, access to more advanced technology and more stable political conditions. To understand how such labor mobility can actually be growth-enhancing to the home country, imagine a stylized economy in which: (i) heterogeneous workers make educational decisions to maximize expected payoffs; (ii) technological progress depends on the composition of human capital; (iii) migration is not a certainty. The rationale behind this is that allowing skilled workers to migrate entices more individuals to invest in education because of the potentially higher payoffs abroad while only a proportion of them can successfully land so that the ex post domestic composition of human capital may, in fine, be improved to be superior to its autarkic one. With a high ex ante fraction of unskilled workers, despite the departure of some skilled workers, a marginal increase in migration possibility will retain more human capital in the home country to foster the economic growth.

Human capital has been considered as a central determinant of long-run economic growth (Nelson and Phelps, 1966; Romer, 1986; Lucas, 1988). To emphasize the crucial role of human capital in economic growth, we focus on how the composition of human capital is determined rather than the level of human capital. Both theoretical and empirical work have provided insight and evidence on the effect of heterogeneous human capital on growth (Krueger and Lindahl, 2001; Krueger and Kumar, 2004). In this model, there are three types of workers: unskilled, generalists and specialists. The skilled workers are not treated homogeneously in a sense that it consists of generalists who have knowledge in multiple fields and innovate independently, and specialists who are adept in a single area and innovate cooperatively. The composition of human capital is characterized by different fractions of these three types of workers. The migration effect is therefore analyzed under four distinct kinds of compositions: unskilled equilibrium, generalists equilibrium, mixed equilibrium and specialists equilibrium. The model implies the home country can have a higher potential growth rate due to the superior composition of human capital with migration prospect. Furthermore, the possibility of migration can counter-intuitively help poor countries escape from a poverty trap.

This model also features an endogenous educational decision and a dynamic technological advancement. Workers decide investments in education depending on existing technology stock and their innate abilities while technological progress is determined by the structure of educated workers. Educational decisions influence the composition of human capital hence the technology and economic growth, and the upgraded technology in return directs future workers' educational decisions to form a dynamic transition. Using this framework, the model captures the dynamic effects of migration as a potentially permanent boost to the economic development of developing countries.

The sufficient conditions for a beneficial migration derived from this model helps to explain why developed countries are more vulnerable to the brain drain effect than developing countries. The analysis in this model shows that a country with a relatively low ex ante fraction of unskilled labor is more likely to suffer a decline in growth should it open to migration. Developed countries with higher fraction of educated workers should focus on retaining skilled workers to prevent the domestic economy from a possibly detrimental brain drain.

1.1 Literature Review

This paper is mainly related to the human capital and endogenous growth literature and the migration or brain drain literature. The crucial role of human capital in economic growth has been investigated extensively. Notably, Romer (1986, 1990), Lucas (1988) and Galor and Tsiddon (1997) have provided theoretical analysis about the interaction between human capital, technological progress and economic development. Empirically, Barro (1991), Mankiw et al. (1992), Benhabib and Spiegel (1994), Schoellman et al. (2010) and Hanushek (2013) have shown the positive relationship between either the level or the quality of human capital and economic growth. This paper continues to explore the research field by focusing on the composition of human capital and economic growth with a migration prospect.

Since human capital is traditionally regarded as a key determinant in economic growth, the departure of skilled labor with high level of human capital or so-called 'brain drain' presumably hurts the home countries (Bhagwati and Hamada, 1974; Haque and Kim, 1995; Chen, 2006). However, recent research studies including Stark et al. (1997), Beine et al. (2001), Dos Santos and Postel-Vinay (2003) have shown that migration prospect can provide incentives for beneficial human capital accumulation and promote the home country's economic growth.

In addition to those literature, the two most relevant migration articles are Mountford (1997) and Di Maria and Stryszowski (2009). Mountford's paper has examined the migration effect both theoretically and empirically to show that the source countries can actually increase the level of human capital as migration becomes possible. As distinct from his work, the model in this paper adopts an endogenous technological progress which depends on workers' educational choices. This enables us to investigate the migration effect not only as a direct influence on economic growth but also as a dynamic stimulus to technology which is the engine of growth. Moreover, in contrast to the workers' homogeneous skill accumulation pattern in his work, we allow heterogeneous worker types to further differentiate the composition of human capital and technological innovation. Di Maria and Stryszowski has studied how migration affects the composition of human capital and economic growth in home countries. They conclude that migration has a stronger distortion effect on the accumulation of human capital for countries who are farther away from the technological frontier. Our model differs from theirs in the composition of human capital. We include unskilled workers as well as skilled workers while only skilled workers present in their model. The inclusion of unskilled labor (who are assumed unable to migrate) should not be merely viewed as trivia or generalization because it changes the pattern of endogenous educational decision under migration prospect, hence the technological progress, which leads to a possible beneficial migration scenario when the positive composition effect, rather than the brain drain distortion, pervades in the home country.

The remainder of the paper is organized as follows. In Section 2, the main model is introduced and we characterize different equilibria of the economy by the composition of human capital. We analyze the static effect as well as the dynamic effect of migration on human capital structure and economic growth. Section 3 extends the main model with non-uniform probability of migration and generalized probability of migration. Section 4 concludes.

2 The Model

We consider an endogenous growth model to explain the migration effect on the composition of human capital and economic growth. The economy consists of workers producing intermediate goods and a single firm producing the final good. Workers make decisions to maximize net income and the firm utilizes the right quantities of intermediates to increase productivity. Technology is dynamically advanced by skilled workers. The model shows how migration can benefit the home country when the positive composition effect dominates the negative brain drain effect. A sufficient condition for the existence of an optimal probability of migration is also derived.

2.1 Environment

We represent the workers of the population as a continuum of size 1. A new generation of workers are born in each period and they live for one period only. There is no population growth. Each worker i consumes his net income completely. There are two countries in the economy: home (H) and host (F). The host country is more developed than the home country. We assume only skilled workers are able to migrate from the home country to the host country with an exogenous probability $p \in (0, 1)$. Time is discrete and indexed by t.

2.1.1 Education

An individual can decide whether to invest in education to accumulate skills with an educational cost E or enter directly into the labor force as an *Unskilled* worker. If he chooses to educate himself, there are two complementary skills P and Q available to learn. An individual can acquire both skills to become a *Generalist* or focus on training in a single skill to become a *Specialist*. Both generalists and specialists are *Skilled* workers.

Workers accumulate different skill levels through education. Suppose the worker's skill level is affected by his innate ability and the existing technology level, the skill level function $M_{i,k,t}$ for skilled worker i is given by

$$M_{i,k,t} = X_i^{\beta} A_{t-1}^{\theta} \tag{2.1}$$

$$0 < \beta < 1, 0 < \theta < 1, k \in \{P, Q\}$$

where X_i measures the worker's innate ability and is uniformly distributed, $X_i \in [0, 1]$. A_{t-1} is the existing technology level from last period, $A_{t-1} \geq 1$. β is the ability discount factor which captures counter-productive noises in skill accumulation, such as distraction in the cross-learning process. Bigger β indicates lower efficiency of a worker's innate ability in transiting into skill level. θ indicates the positive intertemporal technology impact on the skill level.

We assume generalists and specialists have different $M_{i,k,t}$ that $\beta_G > \beta_S$ and $\theta_S > \theta_G$. The rationale behind this is straightforward that generalists are punished more in transiting innate abilities into skills because of multitasking while specialists can benefit more from focusing on a single area and delving deeper into the knowledge pool.

Therefore, if we denote $M_{i,t} = \{M_{i,P,t}, M_{i,Q,t}\}$ as worker i's skill level set, the skill level sets of three types of worker, unskilled worker, generalists and specialists, are given as the following.

Unskilled Worker If a worker chooses not to receive education, he becomes an unskilled worker and has zero skill level in either skill P or Q. So his skill level set is $M_{i,t}^U = \{0, 0\}$.

Generalist If a worker chooses to become a generalist, he would devote half of his time to each skill in order to maximize the total skill level accumulated and therefore be skillful in both P and Q skills (but not as skillful as a specialist is in one single area).[3] So a generalist's skill level set is $M_{i,t}^G = \{\frac{1}{2}M_{i,P,t}^G, \frac{1}{2}M_{i,Q,t}^G\}$. Skill level function of generalists is given by

$$M_{i,k,t}^G = X_i^{\beta_G} A_{t-1}^{\theta_G}, k \in \{P, Q\} \tag{2.2}$$

Specialist If a worker chooses to become a specialist, he would be very skillful in one skill but unskilled in the other. So a specialist's skill level set is $M_{i,t}^S = \{M_{i,P,t}^S, 0\}$ if he specializes in skill P or $\{0, M_{i,Q,t}^S\}$ if he specializes in skill Q. And skill level function of specialists is given by

$$M_{i,k,t}^S = X_i^{\beta_S} A_{t-1}^{\theta_S}, k \in \{P, Q\} \tag{2.3}$$

2.1.2 Coordination

Skilled workers are able to innovate and increase the productivity. Both P and Q are needed in the advancement of technology. Since generalists possess both skills, they can innovate independently. However, a specialist only possesses one skill and the firm has to find another specialist with the complementary skill to team them up in innovation activities.[4] Such pairing is costly so the coordination cost $\widetilde{c} \geq 0$ arises. Bigger $\widetilde{c}$ implies higher coordination cost. For the purpose of simplicity in exposition, define $c = 1 + \widetilde{c}$ so that $c \geq 1$ and $c = 1$ implies zero coordination cost for generalists.

[3] The rationale of investing half of his time into each skill will be explained when technology is introduced.

[4] We do not consider pairing a specialist with a generalist here because with a generalist investing only one half of his time in one complementary skill and one half in the other overlapping skill, it will decrease the pairing specialist's gain.

2.1.3 Technological Progress

The technology is progressed by the innovation of skilled workers or a positive shock to the existing technology level (e.g. reverse engineering imports with better technology and recruiting high skilled foreign experts). We specify the dynamics of technology for worker i as the following

$$A_{i,t} = A_{t-1} + c^{-1}(M_{i,P,t}^{\alpha} + M_{i,Q,t}^{\alpha})^{\frac{1}{\alpha}},\ \alpha < 0 \tag{2.4}$$

where $M_{i,P,t}$ and $M_{i,Q,t}$ are the skill levels of two skills P and Q respectively and c is the coordination cost. A_{t-1} is the average technology level in last period that $A_{t-1} = \int_0^1 A_{i,t-1} dX_i$. $1/(1-\alpha)$ is the elasticity of substitution. Since $\alpha < 0$, we have $1/(1-\alpha) < 1$, this ensures that these two skills are complementary in the advancement of technology.

With three different types of workers' skill level sets, we find the technological innovation functions of unskilled workers, generalists and specialists respectively.

Unskilled Worker An unskilled worker without education does not accumulate skill levels in either P or Q, i.e. $M_{i,P,t} = M_{i,Q,t} = 0$.
Therefore

$$A_{i,t}^{U} = A_{t-1}$$

This implies unskilled workers do not contribute anything to technological progress.

Generalist A generalist splits his time equally doing P and Q so that $M_{i,P,t} = \frac{1}{2} X_i^{\beta_G} A_{t-1}^{\theta_G}$ and $M_{i,Q,t} = \frac{1}{2} X_i^{\beta_G} A_{t-1}^{\theta_G}$. The technological innovation function of generalists is given by

$$A^G_{i,t} = A_{t-1} + c^{-1}\left((\frac{1}{2}X_i^{\beta_G}A_{t-1}^{\theta_G})^\alpha + (\frac{1}{2}X_i^{\beta_G}A_{t-1}^{\theta_G})^\alpha\right)^{\frac{1}{\alpha}}$$
$$= A_{t-1} + 2^{\frac{1-\alpha}{\alpha}}X_i^{\beta_G}A_{t-1}^{\theta_G} \tag{2.5}$$

Note generalists devote half of his time to each skill in order to maximize the innovation outcome.[5] Also recall that since generalists innovate independently, the coordination cost $c = 1$ which means there is no coordination loss in innovation.

Specialist Specialists share their skill level sets in technology innovation activities. We assume that a specialist i accumulating P skill will team up with another specialist j possessing similar ability who is adept in skill Q (i.e. $X_{i,P} = X_{j,Q} = X_i$).[6] So the actual skill level set employed in specialist i's innovation is $\{M^S_{i,P,t} = X_i^{\beta_S}A_{t-1}^{\theta_S}, M^S_{j,Q,t} =$

[5]To maximize the innovation outcome, it's equivalent to

$$Max\ (\tau X_i^{\beta_G}A_{t-1}^{\theta_G})^\alpha + \left((1-\tau)X_i^{\beta_G}A_{t-1}^{\theta_G}\right)^\alpha$$

First order conditions give $\alpha X_i^{\beta_G}A_{t-1}^{\theta_G}(\tau X_i^{\beta_G}A_{t-1}^{\theta_G})^{\alpha-1} = \alpha X_i^{\beta_G}A_{t-1}^{\theta_G}\left[(1-\tau)X_i^{\beta_G}A_{t-1}^{\theta_G}\right]^{\alpha-1}$. Thus, the optimal $\tau = \frac{1}{2}$.

[6]We assume a specialist can always find another specialist in complementary skill with similar ability level, i.e. Positive Assortative Matching (PAM). To have PAM, a sufficient and necessary condition is supermodularity. See Eeckhout and Kircher (2010).
Since $A^S_{i,t} = A_{t-1} + c^{-1}\left((X_{i,P}^{\beta_S}A_{t-1}^{\theta_S})^\alpha + (X_{j,Q}^{\beta_S}A_{t-1}^{\theta_S})^\alpha\right)^{\frac{1}{\alpha}}$,

$$\frac{\partial^2 A^S_{i,t}}{\partial X_{i,P}\partial X_{j,Q}} = c^{-1}\beta_S^2(1-\alpha)\left((X_{i,P}^{\beta_S}A_{t-1}^{\theta_S})^\alpha + (X_{j,Q}^{\beta_S}A_{t-1}^{\theta_S})^\alpha\right)^{\frac{1}{\alpha}-2}(X_{i,P}X_{j,Q})^{\alpha\beta_S-1}A_{t-1}^{2\alpha\theta_S}$$

Supermodularity requires $\frac{\partial^2 A^S_{i,t}}{\partial X_{i,P}\partial X_{j,Q}} > 0$ which implies $\alpha < 1$. This is indeed satisfied by the complementarity of skills condition imposed before that $\alpha < 0$. In fact, there is an equivalence between supermodularity and a standard notion of complementarity, increasing differences. Despite the cardinal property of supermodularity and the ordinal property of complementarity, complementarity implies supermodularity. See Topkis (1998) *Supermodularity and Complementarity*, Chapter 2. Supermodularity ensures Positive Assortative Matching that specialist possessing high ability in skill P will match with specialist in skill Q who also possesses high ability.

$X_i^{\beta_S} A_{t-1}^{\theta_S}\}$. Therefore, the technological innovation function of specialist i is given by

$$\begin{aligned} A_{i,t}^S &= A_{t-1} + c^{-1}\left((X_i^{\beta_S} A_{t-1}^{\theta_S})^\alpha + (X_i^{\beta_S} A_{t-1}^{\theta_S})^\alpha \right)^{\frac{1}{\alpha}} \\ &= A_{t-1} + 2^{\frac{1}{\alpha}} c^{-1} X_i^{\beta_S} A_{t-1}^{\theta_S} \end{aligned} \tag{2.6}$$

Inspecting these three innovation functions, it is obvious that skilled workers generate higher productivity than unskilled workers. However, it is not straightforward to see whether generalists are more productive than specialists in innovation activities. The firm employs the production technology consisting of all three possible technological innovations.

2.1.4 Production and Price

The economy has a perfectly competitive market of the final product Y which is produced from a continuum of mass 1 of intermediate goods g_i. Workers act as local monopolists in providing the intermediates. Each worker produces one variety of g_i according to his innate ability. The Cobb-Douglas production function of final product Y is given by

$$Y_t = \int_0^1 A_{i,t}^{1-\rho} g_{i,t}^{\rho} dX_i, \rho \in (0,1) \tag{2.7}$$

where $A_{i,t}$ is the technology coefficient adopted by ith worker in producing intermediate good at time t, $A_{i,t} \geq 1$ and $g_{i,t}$ is the unit of intermediate good used in final good production at time t.

Assume intermediate goods are produced from the final product according to a one-for-one technology and given that the final product market is competitive, the price of an intermediate good g_i is just its marginal product

$$p_{i,t} = \frac{dY_t}{dg_{i,t}} = \rho A_{i,t}^{1-\rho} g_{i,t}^{\rho-1} \tag{2.8}$$

2.1.5 Income

Assume each worker chooses some quantity of intermediate good $g_{i,t}$ to produce. His net income is given by

$$I_{i,t} = p_{i,t}g_{i,t} - g_{i,t} \tag{2.9}$$

By substituting the price of $g_{i,t}$, we have

$$I_{i,t} = \rho A_{i,t}^{1-\rho} g_{i,t}^{\rho} - g_{i,t} \tag{2.10}$$

A worker's income depends on the quantity of intermediate goods produced and the current technology level adopted in production.

2.1.6 Migration

Skilled workers are assumed to be equally treated in regard to the qualification of migration so that each worker has an uniform probability p to migrate from the home country to the host country. This migration probability is exogenously determined by either the home country via exit visas or the host country via immigration visas. We also assume the home country has a small economy so that p is independent of the population of eligible migrants. The migration policy is perfectly anticipated by each worker.

To provide incentives for migration, we assume the host country always has a higher existing technology level than the home country (i.e. $A_{F,t-1} > A_{H,t-1}$) so that skilled workers can potentially be more productive and earn a better payoff abroad. We will extend our model by non-uniform probability and generalized probability in section 3.

2.1.7 Time Line

Now we have introduced each element of the model and it might be convenient to see the sequence of actions made by each individual as Figure 1.

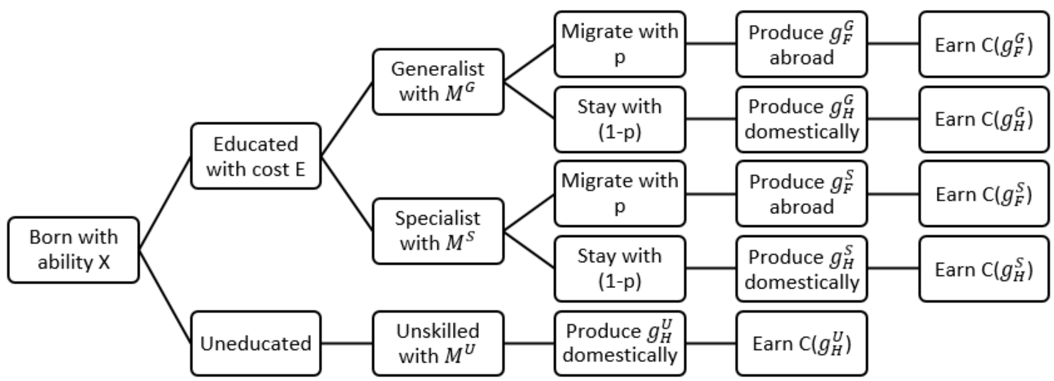

Figure 2.1: Time Line

The next step is to determine the optimal consumption in each possible scenario.

2.2 Workers' Optimization Problem

Each type of worker chooses the quantity of intermediate good $g_{i,t}$ to maximize his net income or consumption $C_{i,t}$ at the equilibrium. The subscript of ability X_i is omitted wherever there is no confusion.

2.2.1 Unskilled Worker

Unskilled workers do not invest in education and they will not migrate to other countries. So the consumption maximization problem for them is

$$Max\ C_{i,t} = I_{i,t} = \rho A_{i,t}^{1-\rho} g_{i,t}^{\rho} - g_{i,t}$$

First order condition with respect to $g_{i,t}$ gives us the optimal quantity of intermediate good and the maximized consumption

$$g_{i,t}^{U*} = \rho^{\frac{2}{1-\rho}} A_{i,t} \tag{2.11}$$

$$C_{i,t}^{U*} = \delta A_{i,t} \tag{2.12}$$

where $\delta = (\frac{1}{\rho} - 1)\rho^{\frac{2}{1-\rho}}$. Plug in the technology level adopted by unskilled workers in the home country, i.e. $A_{i,t} = A_{i,t}^{U} = A_{H,t-1}$. The optimal solution becomes as

$$g_{i,t}^{U*} = \rho^{\frac{2}{1-\rho}} A_{H,t-1} \tag{2.13}$$

$$C_{i,t}^{U*} = \delta A_{H,t-1} \tag{2.14}$$

2.2.2 Skilled Worker

Skilled workers engaging in technological innovation have to pay back their loans on education which is E. So the skilled workers maximize consumption as

$$Max\ C_{i,t} = I_{i,t} - E = \rho A_{i,t}^{1-\rho} g_{i,t}^{\rho} - g_{i,t} - E \tag{2.15}$$

Similar to unskilled workers, we get the optimal quantity of intermediate goods and consumption as

$$g^*_{i,t} = \rho^{\frac{2}{1-\rho}} A_{i,t} \tag{2.16}$$

$$C^*_{i,t} = \delta A_{i,t} - E \tag{2.17}$$

The results look similar to (11) and (12) but they are different in the technological adoption and the possibility of migration. Skilled workers are assumed to migrate to the host countries with an exogenous probability p. We also assume the host country is more developed which implies that the existing technology in the host country is higher than that in the home country, that is $A_{F,t-1} > A_{H,t-1}$. This assumption provides the incentive for skilled workers in the home country to rationally take into account the possibility of earning higher profits abroad while the workers in the host country find it unappealing to work in the home country. Therefore, the optimal quantity of intermediate good will depend on whether he chooses to stay or migrate and his skill type.

As a generalist, if he stays in the home country, he will adopt the technology as $A^G_{i,t} = A_{H,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A^{\theta_G}_{H,t-1}$. If he migrates to the host country, he will adopt a higher existing technology while the skill levels used in the innovation activities are the same since he still accumulates his skills in the home country. So the technology adopted by a migrating generalist is $A^G_{i,t} = A_{F,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A^{\theta_G}_{H,t-1}$. Therefore,

$$g^{G*}_{H,i,t} = \rho^{\frac{2}{1-\rho}} (A_{H,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A^{\theta_G}_{H,t-1})$$
$$g^{G*}_{F,i,t} = \rho^{\frac{2}{1-\rho}} (A_{F,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A^{\theta_G}_{H,t-1})$$

So the expected optimal consumption of a generalist is

$$\begin{aligned}\mathbb{E}[C_{i,t}^{G*}] &= (1-p)\left[\delta(A_{H,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A_{H,t-1}^{\theta_G}) - E\right] + \\ & p\left[\delta(A_{F,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A_{H,t-1}^{\theta_G}) - E\right] \\ &= \delta\left[pA_{F,t-1} + (1-p)A_{H,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A_{H,t-1}^{\theta_G}\right] - E \qquad (2.18)\end{aligned}$$

Recall the technological innovation function of specialists as $A_{i,t}^S = A_{t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{t-1}^{\theta_S}$. Following similar argument as above, the optimal quantities of intermediate good for specialists staying and migrating, respectively, are

$$\begin{aligned}g_{H,i,t}^{S*} &= \rho^{\frac{2}{1-\rho}}(A_{H,t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{H,t-1}^{\theta_S}) \\ g_{F,i,t}^{S*} &= \rho^{\frac{2}{1-\rho}}(A_{F,t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{H,t-1}^{\theta_S})\end{aligned}$$

And the expected optimal consumption of a specialist is

$$\begin{aligned}\mathbb{E}[C_{i,t}^{S*}] &= (1-p)\left[\delta(A_{H,t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{H,t-1}^{\theta_S}) - E\right] + \\ & p\left[\delta(A_{F,t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{H,t-1}^{\theta_S}) - E\right] \\ &= \delta\left[pA_{F,t-1} + (1-p)A_{H,t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{H,t-1}^{\theta_S}\right] - E \qquad (2.19)\end{aligned}$$

2.3 Education Decision

Each worker makes educational decision based on potential maximum consumption. By comparing the payoffs of three different types of worker, we can determine the cutoff innate ability levels of being an unskilled worker, a generalist or a specialist so that the human capital structure is revealed.

2.3.1 Unskilled Worker vs Generalist

By comparing the optimal consumption of unskilled workers and generalists, we can determine the cutoff ability level between them. Equating (14) and (18) gives us

$$X^*_{u,g} = \left[\frac{E - \delta p(A_{F,t-1} - A_{H,t-1})}{2^{\frac{1-\alpha}{\alpha}}\delta A^{\theta_G}_{H,t-1}}\right]^{\frac{1}{\beta_G}} \tag{2.20}$$

A worker with an innate ability higher than this cutoff level, i.e. $X > X^*_{u,g}$, will become as a generalist. If his ability is lower than this level, he will choose to be an unskilled worker. The worker is indifferent if $X = X^*_{u,g}$.

2.3.2 Unskilled Worker vs Specialist

Similarly, we equate (14) and (19) to find the cutoff ability level between unskilled workers and specialists which is

$$X^*_{u,s} = \left[\frac{E - \delta p(A_{F,t-1} - A_{H,t-1})}{2^{\frac{1}{\alpha}}c^{-1}\delta A^{\theta_S}_{H,t-1}}\right]^{\frac{1}{\beta_S}} \tag{2.21}$$

If $X > X^*_{u,s}$, the worker will choose to become as a specialist; if $X < X^*_{u,g}$, he will decline education and be an unskilled worker; if $X = X^*_{u,g}$, he is indifferent.

2.3.3 Generalist vs Specialist

If we equate (18) and (19), we can find the cutoff ability level between generalists and specialists which is given by

$$X^*_{g,s} = (2c^{-1}A^{\theta_S-\theta_G}_{H,t-1})^{\frac{1}{\beta_G-\beta_S}} \tag{2.22}$$

If $X > X^*_{g,s}$, the worker will prefer to be a generalist; if $X < X^*_{g,s}$, he will choose to become a specialist; if $X = X^*_{g,s}$, he is indifferent.[7]

2.4 Composition of Human Capital and Migration Probability

We should now turn to the big picture of human capital structure of the home country as well as the migration effect on the structure. Skilled workers are assumed to migrate to the host country with probability p. The migration is treated as a random activity so that all skilled workers have the same probability of migration.

2.4.1 Composition of Human Capital

Since we have solved the cutoff ability levels of different types of worker, it is feasible to characterize the composition of domestic human capital by those thresholds. Figure 2 illustrates how the composition of domestic human capital is determined against technology with the possibility of migration.

Unskilled Equilibrium When the existing technology is below A_1, both $X^*_{u,g}$ and $X^*_{u,s}$ are above 1 which implies everyone would choose to be an unskilled worker. Since the population size is 1, the quantity of unskilled workers in the home country is just 1. We define this equilibrium as an unskilled equilibrium (UE) since all workers are unskilled.

Generalist Equilibrium If there is a positive shock (e.g. external intrusion) to domestic technology and A_{t-1} jumps above A_1, the economy will start growing under a generalist equilibrium (GE) where all skilled workers are generalists. The generalists begin to emerge as the productivity increases to the certain point where educational

[7]Here, we need to impose an additional restriction that $c > 2$ to make $X^*_{g,s}$ meaningful. This additional assumption ensures at least some part of $X^*_{g,s}$ is between 0 and 1 as $A_{H,t-1}$ goes from 1 to $+\infty$.

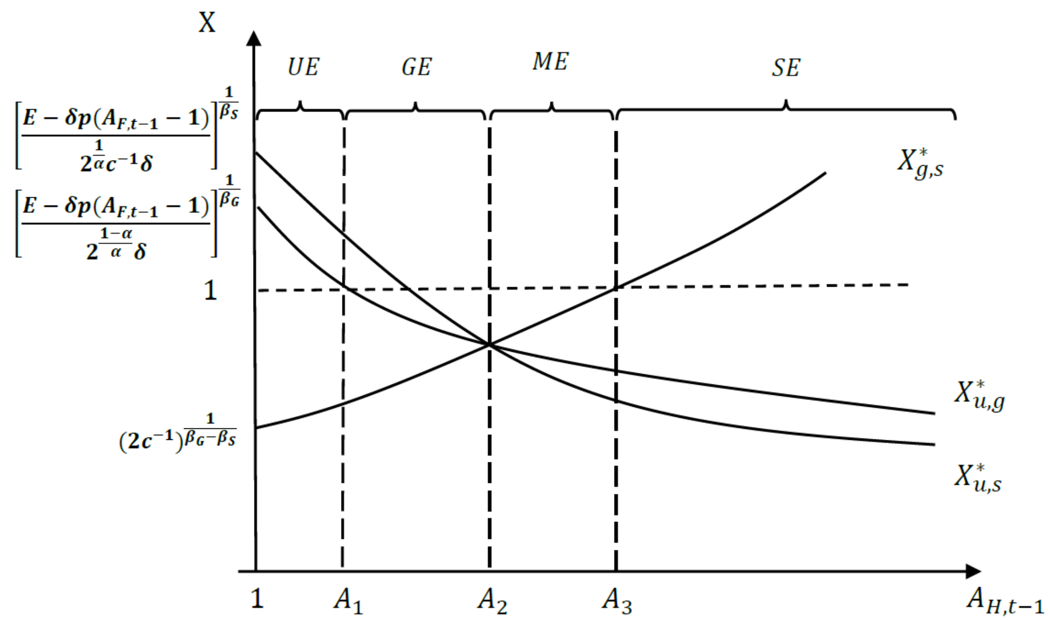

Figure 2.2: Technology and Human Capital Structure

investment is justified. On the graph, this is implied by $X^*_{u,s} > X^*_{u,g} > X^*_{g,s}$.[8] However, only those individuals who possess higher ability levels will become generalists at the beginning. As the technology level grows, more and more unskilled workers with lower abilities become generalists. Since a worker's innate ability is uniformly distributed between 0 and 1 and the population size is 1, the quantity of generalists coincides with its fraction in the composition of human capital. Therefore, with the possibility of migration, the quantity of generalists staying in the home country is $(1-p)(1-X^*_{u,g})$, the quantity of generalists migrating to the host country is $p(1-X^*_{u,g})$ and the quantity of unskilled workers is $X^*_{u,g}$.

Mixed Equilibrium When the existing technology level is above A_2, a new type of skilled worker—specialist—emerges. We define this as a mixed equilibrium (ME)

[8]See Guan Lin (2016) for a detailed discussion.

since generalists and specialists exist contemporaneously in the economy. $X^*_{g,s}$ rises above $X^*_{u,g}$ and $X^*_{u,s}$ is below $X^*_{u,g}$ which implies there are some room for specialists to gain higher payoff than generalists given their abilities are between $X^*_{g,s}$ and $X^*_{u,s}$. Therefore, with the possibility of migration among skilled workers, the quantity of generalists in ME is $(1-p)(1-X^*_{g,s})$, the quantity of specialists is $(1-p)(X^*_{g,s}-X^*_{u,s})$ and the quantity of unskilled workers is $X^*_{u,s}$. It is easy to see that the quantities of unskilled workers and generalists decrease while the quantity of specialists increases as technology grows in ME. The economic rationale behind this is two-fold. Firstly, with larger technology stock, workers accumulates their skills more efficiently and therefore more workers will become skilled workers because of better payoff. Another reason is that workers start to find it more profitable to become specialists because the efficiency gained from concentrating on one task and cooperating in production exceeds the penalty from coordination cost. Consequently, the gain extends as technology grows and more generalists switch to be specialists.

Specialist Equilibrium The division of labor is achieved when $A_{t-1} > A_3$. There will be only specialists as skilled workers in the economy so we define it as a specialist equilibrium (SE). In SE, the quantity of specialists staying is $(1-p)(1-X^*_{u,s})$, the quantity of specialists migrating is $p(1-X^*_{u,s})$ and the quantity of unskilled workers is $X^*_{u,s}$. The number of specialists grows as the technology stock increases. More individuals are encouraged to educate themselves and train as specialists to gain from their comparative advantages.

The dotted lines $X^{**}_{u,g}$ and $X^{**}_{u,s}$ in Figure 3 are the cutoff levels without migration possibility that is $p = 0$.[9] $A_1' > A_1$ and $A_2' > A_2$ imply the economy without migration possibility requires a higher technology stock to enter into GE and ME. This

[9]Since $X_{g,s}$ is not related to p, $X^*_{g,s}$ and $X^{**}_{g,s}$ are the same.

implication emphasizes the major benefit of migration on domestic human capital that migration possibility accelerates the emergence of skilled workers and stimulates domestic technological innovation.

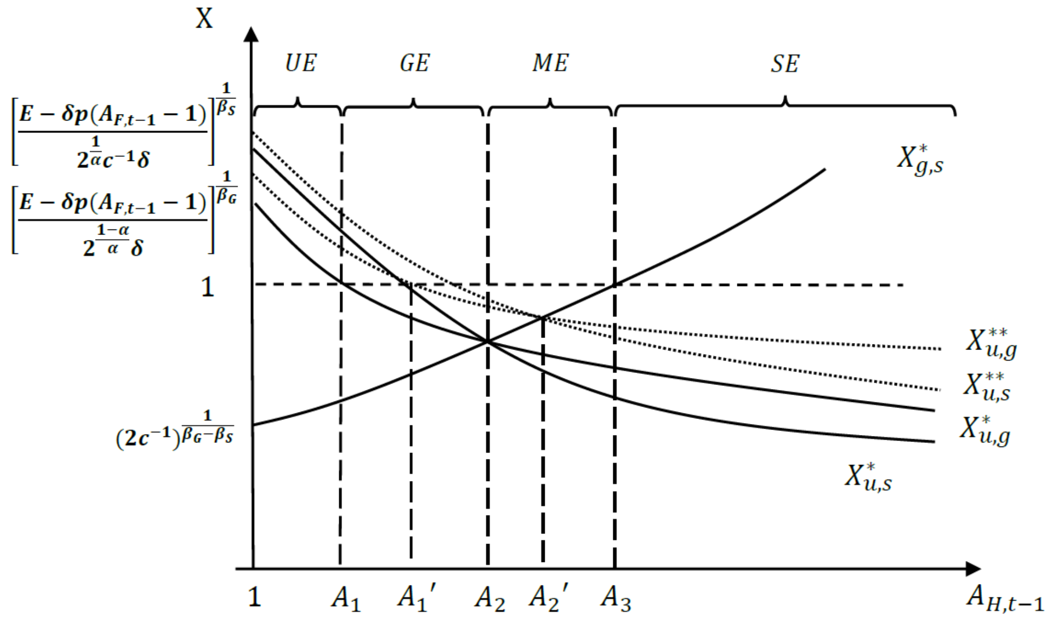

Figure 2.3: Human Capital Structure with Migration

2.4.2 Migration Probability and Human Capital Structure

Now we focus on the effect of migration probability on human capital structure. If we inspect (20) and (21), it is easy to derive that $\frac{\partial X^*_{u,g}}{\partial p} < 0$ and $\frac{\partial X^*_{u,s}}{\partial p} < 0$ which express that the number of skilled workers increases when migration is more likely to happen. However, $X^*_{g,s}$ does not contain p in it which implies the fraction of generalists is not influenced by the possibility of migration in ME. The reason behind this is that in this model the essence of migration is providing a higher start-up technology $A_{F,t-1}$ for innovation activities and this affects both generalists and specialists in the same way. Figure 4 shows an illustration for the effects of migration on domestic composition of human capital structure.

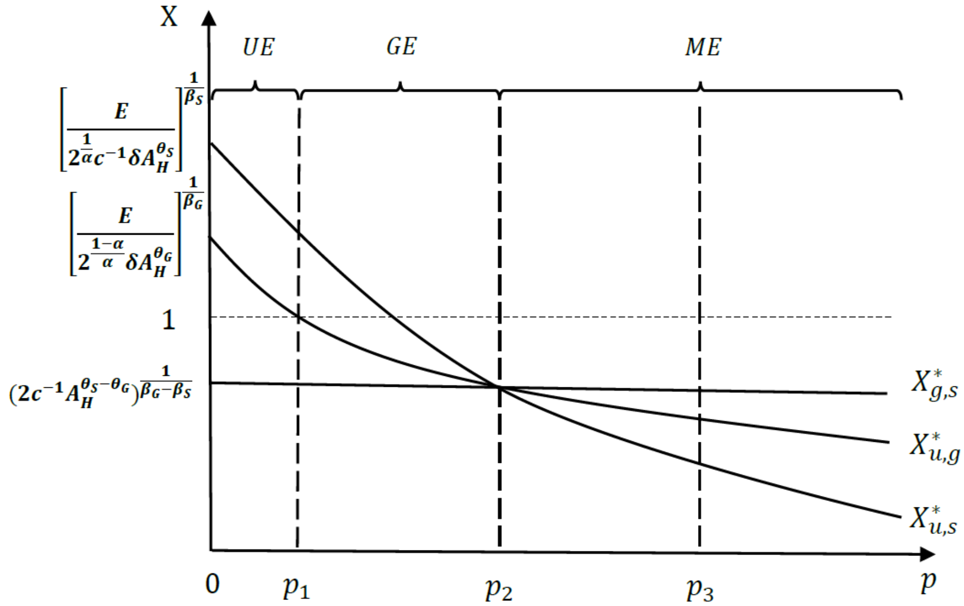

Figure 2.4: Migration Probability and Human Capital Structure

We draw the cutoff ability levels against the probability of migration to explore the properties of domestic human capital structure. We observe that when $p = 0$, i.e. migration is impossible, $X^*_{u,g}$ and $X^*_{u,s}$ are both greater than 1 which implies that all workers will choose to be unskilled workers since even the ablest individual with ability $X = 1$ does not meet the cutoff level to be a skilled worker. As the probability of migration becomes bigger, $X^*_{u,g}$ and $X^*_{u,s}$ decline but are still above 1 until $p = p_1$. The economy in the range $[0, p_1]$ is an unskilled equilibrium since all workers in this equilibrium are unskilled workers.

If we raise p above p_1, the composition of domestic human capital begins to change as $X^*_{u,g}$ is smaller than 1. The workers in the "upper-tail" of the ability spectrum find it optimal to invest in generalist education. Although some workers may realize that specialists are also better than unskilled workers since $X^*_{u,s} < 1$ as p approaches closer to p_2, they will still choose to become generalists because of higher expected payoff implied by $X^*_{u,s} > X^*_{u,g} > X^*_{g,s}$. Consequently, there will be both unskilled workers and generalists existing in domestic human capital structure and the economy is under GE. Therefore, in GE the number of generalists increases and the number of unskilled workers decreases as the migration probability rises. The economic intuition behind this is straightforward that foreseeing a higher migration chance and better expected payoffs more workers will consider to invest in education.

If the home country faces an even higher $p > p_2$, specialists begin to emerge in the composition of domestic human capital so the economy is in ME. We pick $p = p_3$ to illustrate the change in human capital structure. At $p = p_3$, $X^*_{g,s} > X^*_{u,s}$ which implies that workers with abilities higher than $X^*_{g,s}$ will become generalists and those with abilities between $X^*_{g,s}$ and $X^*_{u,s}$ will become specialists. $X^*_{u,g}$ is irrelevant here because workers with abilities lower than $X^*_{g,s}$ will always prefer specialists over generalists. In ME, the number of generalists remains constant while the number of specialists keeps growing as p increases so the fraction of skilled workers inclines and the fraction of unskilled workers declines.

In this model, migration provides an incentive for domestic workers to invest in education so that the human capital structure moves towards a more skill-based workforce.

2.5 Migration Effects on Economic Growth

It is widely discussed that migration can affect a country's economy either positively or negatively, such as brain drain and brain gain.[10] The following analysis explores the effects of migration on home country's economic growth under different equilibria. Since the production function is linearly related to technology at the equilibrium, the growth rate of output is the same as the growth rate of technology.[11] The domestic growth rate of technology $r_{A,t}$ at time t is given by

$$r_{A,t} = \frac{A_{H,t} - A_{H,t-1}}{A_{H,t-1}} \tag{2.23}$$

The technology in the home country $A_{H,t}$ depends on the composition of domestic human capital.

We begin with the discussion on the static effect of migration on the economic growth to analyze how the domestic growth rate changes given a specific migration probability, then we focus on the dynamic effect to see how the economic development is affected over time.

2.5.1 Static Effects of Migration

We start with UE where migration does not play a role since only skilled workers are allowed to migrate in our assumption. In unskilled equilibrium, all workers are unskilled workers so the growth rate in UE is given by

$$r^{ue}_{A,t} = \frac{A^{ue}_{H,t} - A_{H,t-1}}{A_{H,t-1}} = \frac{A_{H,t-1} - A_{H,t-1}}{A_{H,t-1}} = 0 \tag{2.24}$$

[10] See Miyawagi (1991) and Mountford (1997).

[11] At the equilibrium, we have $g^*_{i,t} = \rho^{\frac{2}{1-\rho}} A_{i,t}$ so that $Y^*_t = \int_0^1 A^{1-\rho}_{i,t} g^{*\rho}_{i,t} dX_i = \int_0^1 \rho^{\frac{2\rho}{1-\rho}} A_{i,t} dX_i = \rho^{\frac{2\rho}{1-\rho}} A_t$. The growth rate of output is $r_{Y,t} = \frac{Y^*_t - Y^*_{t-1}}{Y^*_{t-1}} = \frac{A_t - A_{t-1}}{A_{t-1}} = r_{A,t}$.

Therefore, the migration effect on the growth rate of an UE economy is zero. However, we should not regard this result as a claim of seclusion. It rather shows openness can never be detrimental to an economy under UE. Moreover, the migration prospect is very likely to encourage educational investment and therefore potentially push the economy into GE with a positive growth.

The prospect of migration starts to influence the economy as skilled workers emerge. We pick GE to demonstrate the static effect of migration. The composition of human capital in GE consists of generalists, who innovate independently, and unskilled workers who continue to use the existing technology. There will be a part of generalists migrating to the host country so the remaining population in the economy should change correspondingly. Therefore, the average technology level in the current period is given by

$$\begin{aligned} A_{H,t}^{ge} &= \int_0^{X_{u,g}} A_{i,t}^{U} dX_i + (1-p)\int_{X_{u,g}}^{1} A_{i,t}^{G} dX_i \\ &= A_{H,t-1}(1-p+pX_{u,g}) + \frac{2^{\frac{1-\alpha}{\alpha}} A_{H,t-1}^{\theta_G}(1-p)(1-X_{u,g}^{1+\beta_G})}{(1+\beta_G)} \end{aligned} \tag{2.25}$$

So the growth rate in GE is

$$r_{A,t}^{ge} = \frac{2^{\frac{1-\alpha}{\alpha}} A_{H,t-1}^{\theta_G-1}(1-p)(1-X_{u,g}^{1+\beta_G})}{(1+\beta_G)} - p(1-X_{u,g}) \tag{2.26}$$

If we inspect $r_{A,t}^{ge}$ closely, we can break it into two parts: a positive migration effect and a negative one.

$$r_{A,t}^{ge} = \underbrace{\frac{2^{\frac{1-\alpha}{\alpha}} A_{H,t-1}^{\theta_G-1}(1-p)(1-X_{u,g}^{1+\beta_G})}{(1+\beta_G)}}_{\textit{Positive Effect}} - \underbrace{p(1-X_{u,g})}_{\textit{Negative Effect}}$$

The positive effect, or composition effect, arises from the increased fraction of generalist staying in the home country induced by migration possibility and better payoffs abroad for skilled workers. However, a negative effect — 'brain drain effect', is due to the departure of some generalists. Figure 5 plots both effects against the migration probability to illustrate there exists an optimal p^* at which the growth rate is maximized.

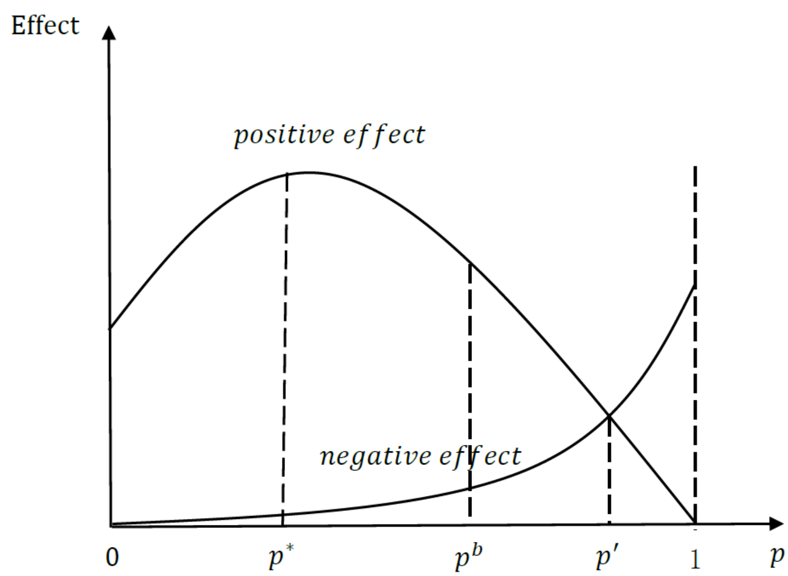

Figure 2.5: Migration Probability and Effects

The distance between the 'positive effect' curve and the 'negative effect' curve is the growth rate in GE. Therefore, we take both effects into account and assess the net effect of migration on growth. Note that it is not necessary that the growth rate is maximized at the peak of the positive effect because the slope of the negative effect might be greater than the slope of the positive effect before the peak. Depending on the parameters in the model, it is also possible for a corner solution that $p^* = 0$ which implies the home country is too vulnerable to the brain drain effect so that it is always growth-reducing to allow migration. The condition derived for an interior solution of p^* existing between 0 and 1 is $X^{**}_{u,g} > \tilde{X}$, where $\tilde{X} = \frac{A_{H,t-1}\delta\beta_G(1+\beta_G+2^{\frac{1-\alpha}{\alpha}}A^{\theta_G-1}_{H,t-1})}{E\beta_G+(1+\beta_G)(A_{F,t-1}-A_{H,t-1})\delta+(1+\beta_G)A_{H,t-1}\delta\beta_G}$. Hence, $X^{**}_{u,g} < \tilde{X}$ is the condition for a corner solution.[12] The economic intuition behind this is that if, in the absence of migration, the autarkic economy has a low fraction of generalists and its fraction of unskilled labor is greater than $\tilde{X}$ then it is beneficial to open the gate and allow domestic skilled workers to migrate. There exists a p^* at which composition effect extremely dominates the brain drain effect and the growth rate is maximized. On the other hand, if the home country already has an ex ante significant fraction of generalists, migration possibility could be detrimental to the domestic economy because of the saturation in generalists and the substantial loss of skilled workers. This result coincides with many empirical findings which indicate that a positive linkage between migration and economic growth only exists in countries with low probabilities of migration and low levels of human capital.[13]

Two further corollaries follow due to $\frac{\partial \tilde{X}}{\partial A_{F,t-1}} < 0$ and $\frac{\partial \tilde{X}}{\partial E} < 0$. The first one implies that if the host country has higher existing technology level, the threshold would be lower and migration is more likely to be beneficial. The intuition is straightforward that a relatively large technological gap between home country and host country would magnify the positive composition effect of migration more than the negative brain drain effect. The second corollary is that migration tends to benefit the economy if the home country has relatively higher education cost. We might explain this counter-intuitive conclusion from an extreme case where the educational cost in the home country is zero (i.e. education is fully subsidized) and therefore all workers in the economy are generalists. Any migration probability would be detrimental to the economy because there is no room for further improving the domestic composition of

[12]See Appendix B.1 for detailed calculation.

[13]For example, see Lien and Wang (2005) and Beine et al. (2008).

human capital while generalists are leaving the country. These two corollaries exactly explain why developed countries are concerned with brain drain effect more than the developing countries. Being a technological leader and providing plentiful allowance in education, developed countries who have relatively low fraction of unskilled workers are more vulnerable to the departure of domestic skilled workers.

Suppose the interior solution exists then the economic growth is maximized at p^* in Figure 6 where the positive effect of migration strongly dominates the brain drain effect. There is a break-even probability p^b at which the economy is indifferent with or without migration. So any migration probability above p^b will lead the economy into a worse growth path than its original one without migration. The growth rate can even be negative if the country has a very high $p > p'$. Consider an extreme case when $p = 1$, that is all generalists will migrate. The massive brain drain will leave the home country with a reduced labor force consisting of only unskilled workers which could potentially lead the country back into UE with a decreased technology stock, hence a negative growth in productivity.

The analysis of migration's static effect on the growth rate in ME or SE is similar to that of GE that if the ex ante domestic fraction of skilled workers is below a certain threshold, migration has a beneficial effect on the growth rate that there is an optimal probability p^* at which the home country achieves the maximum growth rate and a break-even probability p' at which the home country grows the same as it does without migration.[14]

A final note to this subsection is that the optimal probability of migration p^* is changing at each date t as p^* is obviously related to $A_{H,t-1}$ which grows over time. It is not hard to derive that the beneficial migration threshold increases as $A_{H,t-1}$ increases. Moreover, the domestic fraction of unskilled worker declines as the economy

[14] See Appendix B.2 for thresholds calculation.

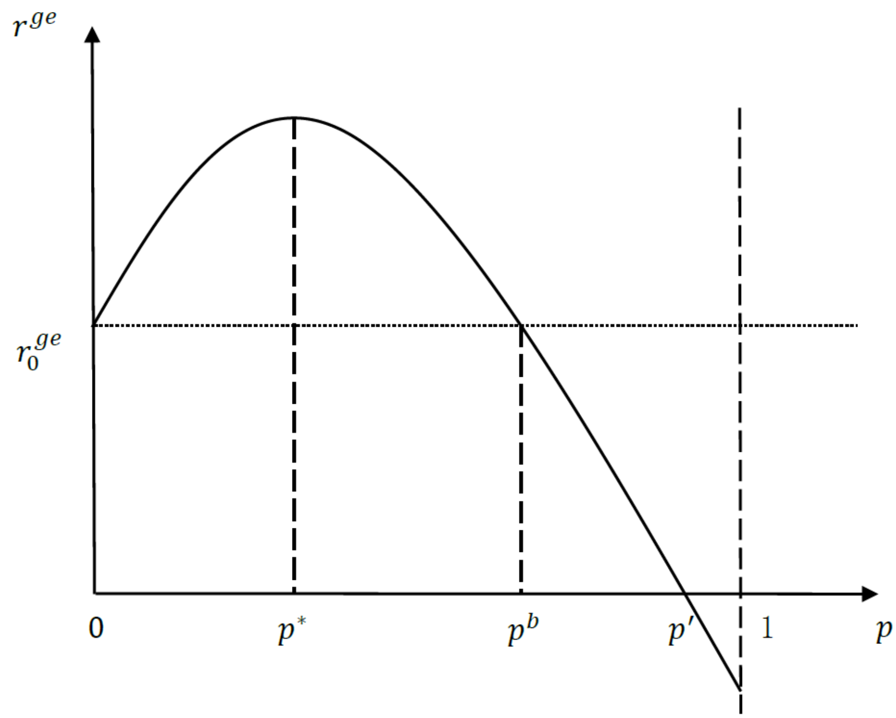

Figure 2.6: Migration Probability and Growth Rate in GE

develops. Therefore, it is more and more likely that the optimal migration probability becomes non-existent between 0 and 1 which implies the home country tend to have a distortion rather than a benefit from migration as the domestic economy grows to the higher end of the economic stage spectrum.

2.5.2 Dynamic Effects of Migration

Now we turn to the dynamic effects of migration on economic growth.[15] The dynamics in this model is due to the endowment of existing technology level. Implementing a migration policy at time t^* will influence workers' educational decisions

[15]Here again, we are more interested in the case when $X_{u,g}^{**} > \tilde{X}$ so the following analysis shows how migration has a positive dynamic effect on growth.

and consequently change the composition of human capital and the advancement of technology. The affected technology level under the migration prospect will in turn cause another change in the composition of human capital and technological innovation. The dynamic effect of migration is a permanent influence on the home country's economic development.

The dotted line in Figure 7 illustrates the growth rate path over time without migration possibility.[16] The solid line demonstrates the economic growth path with migration.

Suppose the home country opens to global market and allows domestic skilled workers to migrate at time t^* in GE. With a proper migration probability lay in $[0, p^b]$, the growth rate will jump up to a new growth path in GE'. The economy will enter into ME earlier at date $t_1' < t_1$. The intuition behind it is two-fold: on one hand, facing a probability of earning a higher payoff increases the fraction of skilled workers staying in the home country so that the economy grows at higher rate; on the other hand, the migration prospect lowers the threshold of ME which makes specialists emerge earlier. These two effects help the country reach the next economic stage faster. Similarly, the economy enters into SE at t_2' prior to t_2. Although the threshold of SE does not change with the migration (since $X_{g,s}$ is irrelevant of p), the country still reaches SE earlier because of the additional fraction of skilled workers induced by migration possibility.

Figure 8 illustrates how the logarithmic technology level changes with migration over time. At time t^*, the autarkic economy opens to the global labor market. As the growth rate is higher in GE', ME' and SE', the technology level growth follows

[16] See Guan Lin (2016). The shape of growth path is depending on two factors: the number of skilled workers and the level of existing technology. With an acceleration in the growth of skilled workers population in GE and ME and a moderate level of existing technology, the economic growth rate inclines over time. However, the growth rate begins to decline when it reaches the maximum with relatively high technology level in SE. Since the labor force is almost fully specialized, the composition effect of human capital is slowly tapering off and the growth rate asymptotically approaches to zero.

a steeper path which is indicated by the solid line. It is clear that the openness has a permanent beneficial effect on the productivity as long as the economy has a proper migration probability: the level of technology with migration possibility is permanently higher than the level without migration possibility in the limit.

It also shows that if the economy is in UE, migration prospect may lower the threshold of becoming a generalist and encourage workers to invest in education, and therefore lead the country out of the 'poverty trap' with a positive economic growth.

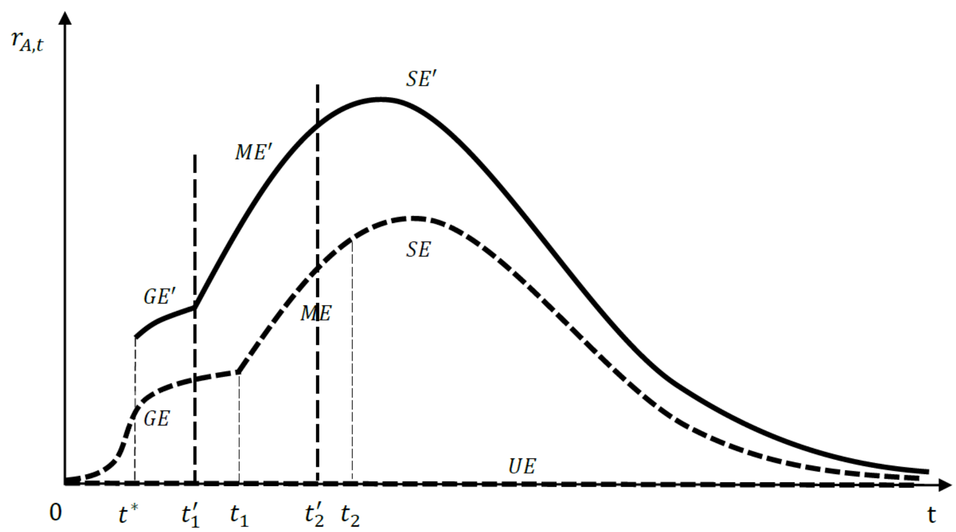

Figure 2.7: Growth Rate Change with Migration Over Time

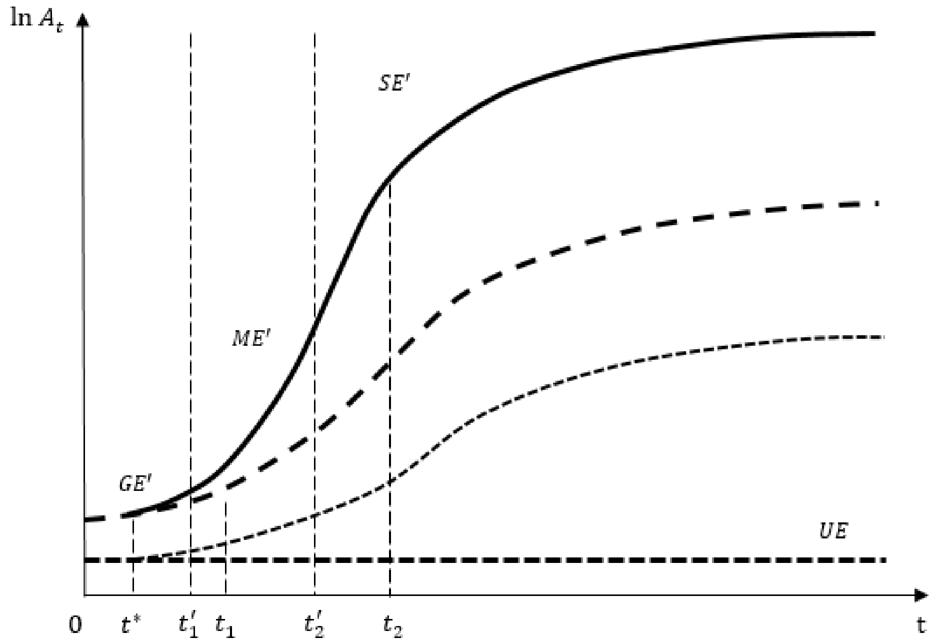

Figure 2.8: Logarithmic Technology Level Change Over Time

3 Model Extensions

3.1 Non-uniform Probability of Migration

So far we have made the assumption that different types of skilled worker migrate with the same probability, i.e. a uniform probability p. We now relax the assumption that generalists face the probability p_G and specialists face the probability p_S. We further assume that $p_S > p_G$ which implies specialists are more likely to migrate. Since the migration occurs in one direction from the less developed home country to the more advanced host country, it is very likely that the host country is already at the stage of ME or SE in which specialists are favored over generalists. With this non-uniform probability assumption, the expected payoffs of different types of skilled worker change correspondingly,

$$\mathbb{E}[C_{i,t}^{G*}] = \delta\left[p_G A_{F,t-1} + (1-p_G)A_{H,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A_{H,t-1}^{\theta_G}\right] - E \tag{3.27}$$

$$\mathbb{E}[C_{i,t}^{S*}] = \delta\left[p_S A_{F,t-1} + (1-p_S)A_{H,t-1} + 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{H,t-1}^{\theta_S}\right] - E \tag{3.28}$$

Therefore, we get the new cutoff ability levels

$$X_{u,g}^{***} = \left[\frac{E - \delta p_G(A_{F,t-1} - A_{H,t-1})}{2^{\frac{1-\alpha}{\alpha}}\delta A_{H,t-1}^{\theta_G}}\right]^{\frac{1}{\beta_G}} \tag{3.29}$$

$$X_{u,s}^{***} = \left[\frac{E - \delta p_S(A_{F,t-1} - A_{H,t-1})}{2^{\frac{1}{\alpha}} c^{-1}\delta A_{H,t-1}^{\theta_S}}\right]^{\frac{1}{\beta_S}} \tag{3.30}$$

While $X_{g,s}^{***}$ can not be explicitly obtained, it is not hard to prove $X_{g,s}^{***} > X_{g,s}^{*}$.[17] Without loss of generality, we assume $p_G = p$, hence $p_S > p$ so that $X_{u,g}^{***} = X_{u,g}^{*}$ and $X_{u,s}^{***} < X_{u,s}^{*}$. Figure 9 shows the changes in human capital structure. With non-uniform probability of migration, although the economy reaches GE at the same existing technology level as the uniform case, it enters into the stage of ME and SE earlier at A_2'' and A_3'' respectively. The intuition is straightforward that with higher probability to migrate as a specialist more worker will tend to receive specialist education so that the emergence of specialist is advanced.

[17] Compare the implicit forms of $X_{g,s}^{*}$ and $X_{g,s}^{***}$

$$X_{g,s}^{*} : 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A_{H,t-1}^{\theta_G} - 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{H,t-1}^{\theta_S} = 0$$

$$X_{g,s}^{***} : 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A_{H,t-1}^{\theta_G} - 2^{\frac{1}{\alpha}} c^{-1} X^{\beta_S} A_{H,t-1}^{\theta_S} - (p_S - p_G)(A_{F,t-1} - A_{H,t-1}) = 0$$

$(p_S - p_G)(A_{F,t-1} - A_{H,t-1}) > 0$ and $0 < \beta_S < \beta_G < 1$ imply that $X_{g,s}^{***} > X_{g,s}^{*}$.

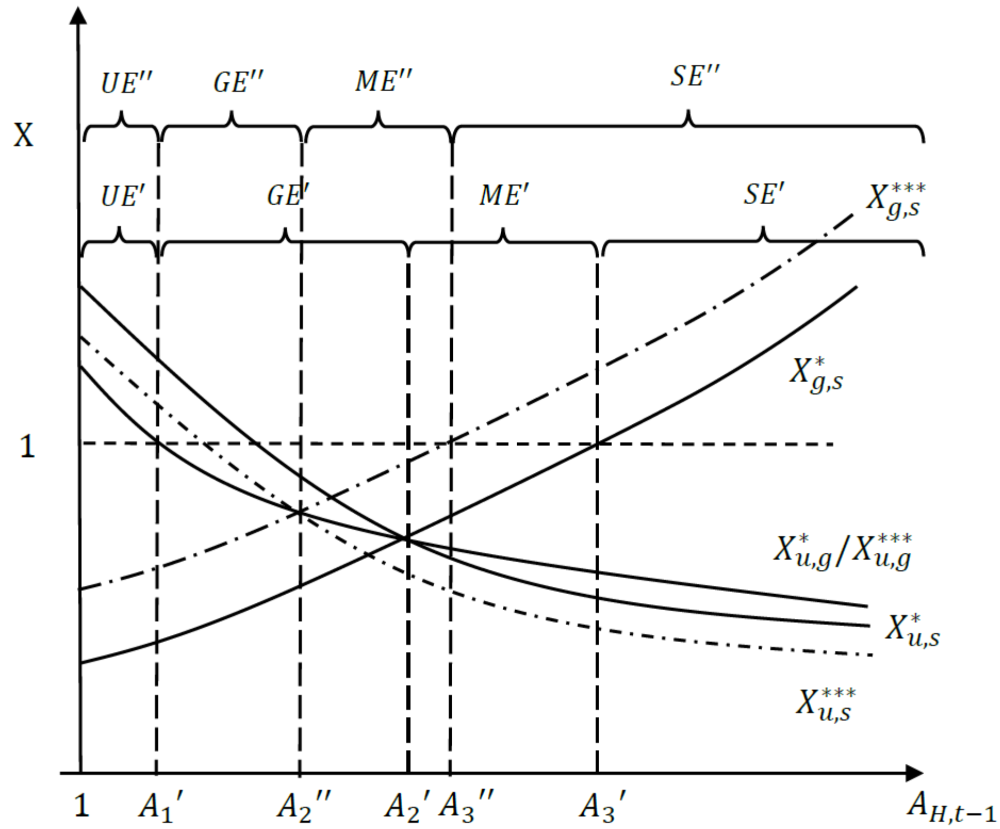

Figure 2.9: Human Capital Structure with Non-uniform Migration Probability

Following a similar argument of uniform probability case, we assume there exists an interior solution of the migration probability between 0 and 1 maximizing the growth rate.[18] The dynamic effect of non-uniform migration on growth is depicted as the top line in Figure 10 and the corresponding changes in technology level are illustrated in Figure 11. The government announces the policy of migration at the same date t^* while specialists have a higher chance to successfully migrate. Since $p_G = p$, the growth rate follows the uniform path until t_1'' at which it enters ME" and follows a steeper path to t_2'' where SE" commences.

[18]In the non-uniform case, we have two probabilities p_G and p_S. So we should assume there exists a p_G^{*ge} maximizing r^{ge}, a p_S^{*se} maximizing r^{se} and a set of $\{p_G^{*me}, p_S^{*me}\}$ maximizing r^{me}.

Technology level is boosted to an even higher level than the uniform case from t_1'' when the economy enters into ME". Thus, the higher migration probability of specialists pushes the economy into next development stage with larger fractions of skilled workers staying in the home country if the ex ante domestic fractions of skilled workers are below a certain threshold.

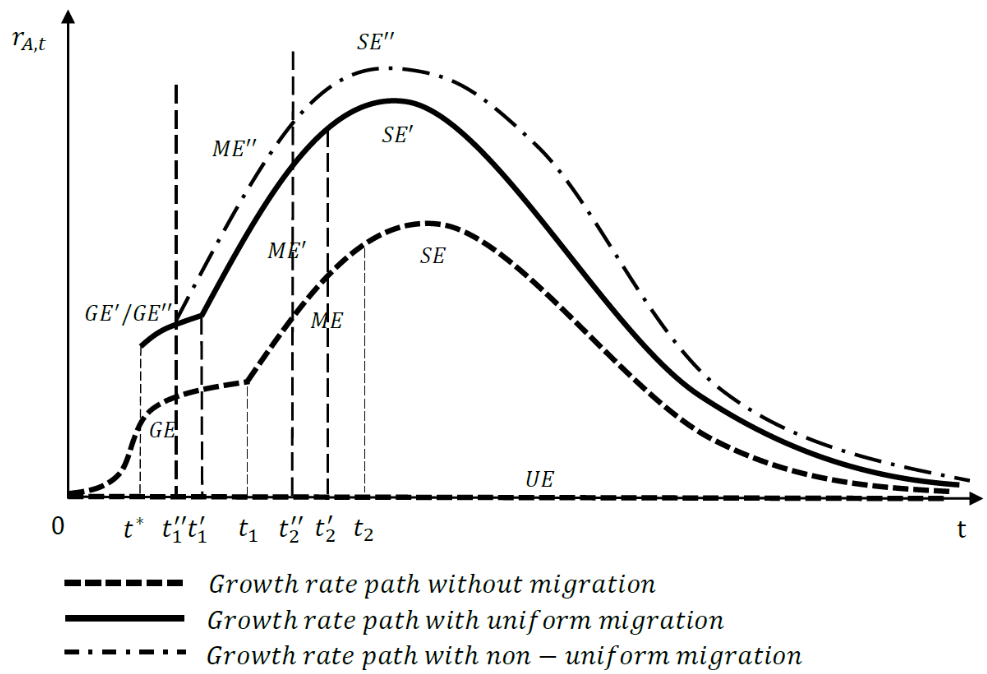

Figure 2.10: Growth Rate Change with Non-uniform Migration Over Time

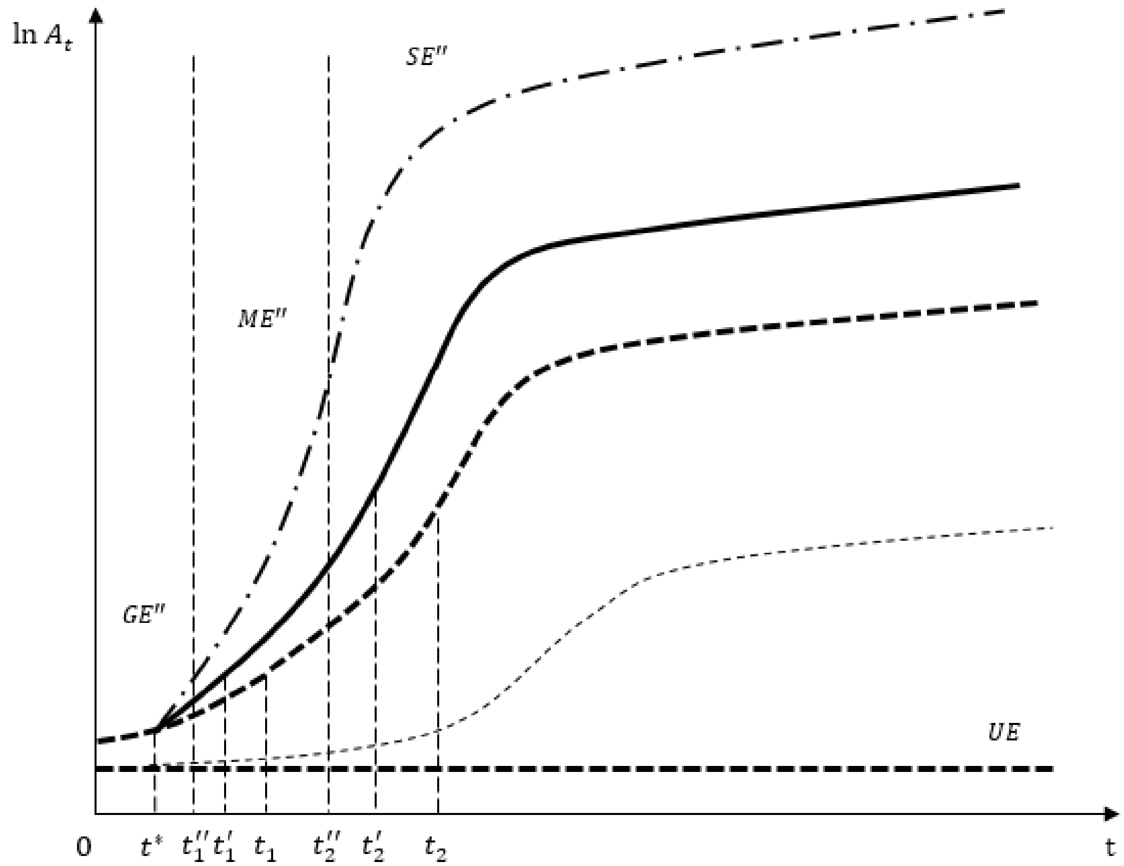

Figure 2.11: Logarithm Technology Level with Non-uniform Migration Over Time

3.2 Generalized Probability of Migration

The prohibition on migration of unskilled workers sometimes seems to be too restricted. Therefore, another natural extension of the basic model is to generalize the probability of migration with an individual's innate ability. Self-selection bias is more likely to present among abler workers. Innate abilities including non-cognitive skills (e.g. adaptability and sociability) and cognitive skills (e.g. IQ) tend to affect the individual probability to move out.[19] This assumption further generalizes the model by allowing all workers to migrate, not just skilled workers. Without making

[19]See Bütikofer and Peri (2016).

the model more complicated, we define the probability of migration for each worker as $p(X) = X$ which implies that the ablest worker whose ability is 1 in the economy will migrate for sure while those who possess 0 ability will not be able to migrate at all.

Since all workers are assumed to migrate with probability $p(X) = X$, the expected payoff for each type becomes

$$\mathbb{E}[C_{i,t}^{U*}] = \delta\left[XA_{F,t-1} + (1-X)A_{H,t-1}\right] \tag{3.31}$$

$$\mathbb{E}[C_{i,t}^{G*}] = \delta\left[XA_{F,t-1} + (1-X)A_{H,t-1} + 2^{\frac{1-\alpha}{\alpha}}X^{\beta_G}A_{H,t-1}^{\theta_G}\right] - E \tag{3.32}$$

$$\mathbb{E}[C_{i,t}^{S*}] = \delta\left[XA_{F,t-1} + (1-X)A_{H,t-1} + 2^{\frac{1}{\alpha}}c^{-1}X^{\beta_S}A_{H,t-1}^{\theta_S}\right] - E \tag{3.33}$$

Solve for the cutoff abilities

$$X_{u,g}^{+} = \left(\frac{E}{2^{\frac{1-\alpha}{\alpha}}\delta A_{t-1}^{\theta_G}}\right)^{\frac{1}{\beta_G}} \tag{3.34}$$

$$X_{u,s}^{+} = \left(\frac{E}{2^{\frac{1}{\alpha}}c^{-1}\delta A_{t-1}^{\theta_S}}\right)^{\frac{1}{\beta_S}} \tag{3.35}$$

$$X_{g,s}^{+} = (2c^{-1}A_{t-1}^{\theta_S-\theta_G})^{\frac{1}{\beta_G-\beta_S}} \tag{3.36}$$

The cutoff abilities are exactly the same as those in autarkic economy. It is not surprising to see the coincidence because allowing the whole labor force to migrate is equivalent to forming a new union country with an average technology level of the home and the host countries. Although the cutoff levels remain the same, the home country now actually possesses an illusory technology stock $A_{H,t-1}^{e} = XA_{F,t-1} + (1-X)A_{H,t-1}$ which is higher than the real domestic technology stock $A_{H,t-1}$. The composition of domestic human capital will change corresponding to $A_{H,t-1}^{e}$ which distorts workers' educational decisions and deviates the growth path from its optimal level. Thus, with a generalized probability of migration, it is always detrimental for the home country's economic development.

3.3 Endogeneity of Migration

The assumption on migration we have made so far is that workers migrate with some exogenous probability p. It is also helpful to discuss the endogeneity of migration given that workers differ in their efforts made to land a successful migration. The effort can be either pecuniary such as the advisory fees paid to migration lawyer, or non-pecuniary such as the time to learn the foreign language and culture. Theses efforts can affect the probability of a successful migration.

Suppose we denote $e \in [0, +\infty)$ as the worker's effort and the migration probability p and the associated costs v both depend on e such that

$$p(e) \in [0,1), p'(e) > 0, p''(e) < 0, p(0) = 0$$
$$v(e) \geq 0, v'(e) > 0, v''(e) > 0, v(0) = 0$$

Then, for example, if he is a generalist, he picks e to maximize the expected payoff given X, E, $A_{F,t-1}$ and $A_{H,t-1}$

$$\begin{aligned} \max_e \quad \mathbb{E}[C_{i,t}^{G*}] &= \Big(1 - p(e)\Big) \Big[\delta(A_{H,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A_{H,t-1}^{\theta_G}) - E - v(e)\Big] + \\ & \quad p(e) \Big[\delta(A_{F,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A_{H,t-1}^{\theta_G}) - E - v(e)\Big] \\ &= \delta \Big[p(e) A_{F,t-1} + \Big(1 - p(e)\Big) A_{H,t-1} + 2^{\frac{1-\alpha}{\alpha}} X^{\beta_G} A_{H,t-1}^{\theta_G}\Big] - E - v(e) \end{aligned} \tag{3.37}$$

First order condition gives

$$\frac{v'(e)}{p'(e)} = \delta(A_{F,t-1} - A_{H,t-1})$$

At the optimal, it is easy to see that $\frac{v'(e^*)}{p'(e^*)}$ increases in e^* so that if $(A_{F,t-1} - A_{H,t-1})$ becomes smaller, e^* decreases and therefore $p(e^*)$ decreases. The intuition behind is that as the technological gap between home and foreign country shrinks, the worker will make less effort in order to migrate. The reason is straightforward that with a similar technology level, there is little difference in earnings between two countries so that workers have less incentive to migrate. As a result, more skilled workers will stay in the home country as domestic technology catches up.

On the other hand, endogenizing p will affect workers' educational decisions and therefore change the distribution of human capital. It is very likely that more fractions of workers will choose to invest in education when the technological gap is relatively large so that the economic growth rate will accelerate at the beginning. As the gap closes up, significantly fewer fractions of workers will invest in education and the growth will slow down sharply compared to the exogenous p case. Thus, endogenizing p will amplify the effects of migration on growth, both positively and negatively.

4 Conclusion

The argument on the effects of migration on domestic human capital structure and economic development is not yet to be settled. This paper contributes to the understanding of a potentially beneficial migration effect that the home country can actually gain faster growth rate with the possibility of migration if its ex ante fraction of unskilled labor is relatively high. The model shows how migration affects domestic human capital structure through a positive composition effect and a negative brain drain effect. Migration prospects provide incentives for uneducated workers to invest in education so that it helps the accumulation of domestic human capital. However, skilled workers depart due to the possibility of migration which reduces the human capital. Migration serves as a double edge sword to the home country's economy. Policy makers in developing countries can use it as an externality to adjust the composition of human capital should it deviate from the equilibrium. Governments in developed countries ought to focus on retaining skilled workers to mitigate the brain drain problem due to the continued globalization.

CHAPTER 3

THE EFFECT OF TERTIARY EDUCATION COMPOSITION ON ECONOMIC GROWTH

1 Introduction

> *The acquisition of such talents, by the maintenance of the acquirer during his education, study, or apprenticeship, always costs a real expense, which is a capital fixed and realized, as it were, in his person. Those talents, as they make a part of his fortune, so do they likewise of that of the society to which he belongs.*
>
> — Adam Smith, *The Wealth of Nations*, 1776

"Human capital" was not widely accepted and even scoffed by economists since many thought people were not to be equated with property and marketable assets (Schultz, 1961). It was not until the late 1960s that the emphasis was placed on the human capital and the term became as part of our lingua franca. Human capital is mainly related to the investment in education: primary, secondary and tertiary[1]. Although primary and secondary education have been well recognized as indisputable factors in the accumulation of human capital and the development of economy, the economic effects of tertiary education is far from settled.

The purpose of this paper is to investigate the effects of different levels of tertiary education on economic growth with dynamic panel data estimation techniques. The

[1] The term "tertiary education" throughout this paper refers to formal education following the completion of a secondary education which includes vocational education and training, undergraduate and postgraduate education. It is also known as further education, continuing education or higher education.

study is conducted by estimating an augmented Solow growth model with secondary, short-cycle/pre-college, bachelor's/master's and doctorate education as added regressors. The stratification of tertiary education enables us to inspect the economic effect of tertiary education from individual parts as well as understand the holistic influence of human capital on economic development.

As the world economy and technology grow rapidly, it is not surprising to see more emerging needs and emphasis on tertiary education, not only in developed countries where primary and secondary education are fully established but also in developing countries experiencing educational revolution.[2] Tertiary education plays its role through three major pathways: teaching, research and innovation, and service. The accumulation of human capital through teaching and research contributes to economic development by increasing productivity and earnings. Endogenous growth theory has explained how highly skilled workers are essential and crucial for economic growth, not just because the higher wages they earn, but also because such personnel accelerates the adaptation and transfer process of technology (Lucas, 1988). Furthermore, universities and other higher education institutions also engage in the development of economy by providing service such as dissemination of knowledge to the public, providing medical and lab services as well as offering available use of the facilities and buildings. Therefore, the positive influence of tertiary education is multifaceted that it benefits the economy in both direct and indirect ways.

However, unlike primary and secondary education, the intrinsic complexity of how tertiary education system interacts with the society makes it difficult to assess its holistic influence on economic development. While a majority of growth literature

[2] According to UNESCO Institute for Statistics, the average gross tertiary education enrollment ratios in developed countries and developing countries have increased 18% and 15%, respectively, from 2000 to 2013. Notably, Albania and Chile both have experienced a substantial surge about 47% in the gross enrollment ratio. During the same period, more than 30% increase was seen in countries such as Czech Republic, Belarus, Saudi Arabia, Mongolia, Slovenia as well as Ukraine.

suggests positive effects of tertiary education on all-around development of a society, the effect of tertiary education on economic growth still remains controversial. For example, Busikova (2013) argues that overheated investment in tertiary education may decline the quality of schools and impose unnecessary pressure on government deficit hence result in inefficient resource allocation. Indeed, research is costly as the significant amount of resources invested in the studies may ultimately yield undesirable or even fruitless outcome. Especially in developing countries, they often have limited resources available to invest in the employment of tertiary-level teaching faculty and the development of education system. The investment strategies of tertiary education can be widely different across countries based on their unique sets of historical, economic and political circumstances.

In this paper, I use a panel data on a group of 77 countries for the period 1998-2011 to estimate the effects of different levels of tertiary education on real GDP per capita. Several dynamic panel data techniques are employed, such as Anderson-Hsiao, the Difference Generalized Method of Moments and the System Generalized Method of Moments, to overcome the endogeneity issue caused by the lagged dependent variable. I cluster the countries into 2 groups: developed country and developing country. I also stratify the tertiary education into 3 levels following ISCED (The International Standard Classification of Education): ISCED level 5 for short-cycle/pre-college education, ISCED level 6&7 for bachelor's/master's education and ISCED level 8 for doctorate education. I find a significantly positive correlation between ISCED level 5 tertiary education and real GDP per capita for both developed and developing countries. An 1 percent increase in the number of short-cycle/pre-college graduates increases real GDP per capita by about 0.01 percent for developed countries and 0.025 percent for developing countries. The study also shows that undergraduate and graduate education are only found positively correlated to economic growth in developed countries. ISCED level 6&7 and level 8 contribute to the economic growth of developed countries by about 0.02 percent and 0.01 percent, respectively. The result suggests that countries from different groups should focus on the development of the provision in different levels of tertiary education based on the contribution of each individual level to the economic growth.

It should be clear that the aim of this paper is to demonstrate the economic contribution of each level in tertiary education, rather than debate over the relative importance of each level. Different levels of tertiary education are clearly not substitutes but complements. Each level of tertiary education is most likely to have externalities on others.

1.1 Literature Review

Robert Solow's (1957) pioneer findings on the residual open the gate of the new era of human capital research. His work demonstrates there is a large portion of economic growth that cannot be explained by the growth of physical capital stock and labor. Numerous papers initiated a great deal of research to discover the role of human capital and its composition.

Most human capital and growth literature finds a positive relationship between education and economic growth at the aggregate level. Mankiw, Romer and Weil (1992) show that most cross-country differences in income per capita can be explained by an augmented Solow model with human capital. The expanded neoclassical growth model of MRW shows countries with faster growth rate of education will achieve faster transitions and higher economic growth. Barro and Lee (1993) find the overall years of male and female school attainment have positive influences on growth rates of real per capita GDP. Evidences of such positive relationship are also found in developing countries by Vinod and Kaushik (2007). The empirical result in their study indicates a one percent increase in literacy increases growth by 1.2 to 4.7 percent. Human capital contributions to economic growth is also founded in India by Viswanath et al. (2009). Using an aggregate production function approach, they find a strong positive relationship between investments in education and growth.

Moreover, scholars have extended their studies into subgroups of education, namely primary education, secondary education and tertiary education. Such breakdown can potentially provide a more specific and informative guidance on educational development. Gyimah-Brempong et al. (2006) use panel data from a sample of 34 African countries for period 1960-2000 and find increased tertiary education has significantly positive impacts on the growth rate of per capita income in African countries. In Ramcharan (2004), he develops an analytical framework to address whether secondary or tertiary education should be promoted in public policy. It claims that developing countries should only invest in secondary education and import high-skilled education embodied in the foreign goods. If educational attainment increases with the level of income, it's most likely that tertiary education is more stressed in developed countries than less developed countries (Hall and Jones, 1999). Storm and Feiock (1999) show that higher education has positive consequences in terms of tangible indicators of state economic performance: earnings, exports and gross state product. Huang (2012) also find there is a massive increase in the numbers of universities in Japan over the period 1965-2007. However, the effect of tertiary education is far from settled. Busikova (2013) argues that growth in tertiary education has many benefits as well as negative impacts through an example of Slovakia. Overheated investment in higher education may decline the quality of schools and impose unnecessary pressure on government deficit hence result in inefficient resource allocation. Reis and Sequeira (2007) also suggest that a negative externality of R&D (hence tertiary education) in human capital accumulation will not only offset the effects of spillovers and returns to specialization but also induce overinvestment in R&D.

Although there has been a considerable amount of discussion on the aggregate effect of tertiary education on economic growth, relatively less attention is given to the effect of composition of tertiary education. Decomposing the tertiary education is a further step towards the understanding of its effect at stratified levels which can be very different with heterogeneous education compositions across countries. For developed countries where primary education and secondary education are almost fully established, it is more crucial for them to shift their focus on setting reasonable composition of tertiary education to meet the needs of increasingly demanding modern economy. As for less developed countries or developing countries, it is wise to consider whether allocating resources in growing tertiary education is rewarding or necessary. Tsai, Hung and Harriott (2010) analyze the effect of human capital composition using five fields of study: agriculture, high-tech, business and service, the humanities, and health and welfare. Their result indicates a significant effect of high-tech human capital on growth. Colombo and Grilli's (2005) work shows that human capital in scientific-technical field is positively related to a firm's performance.

The rest of the paper is organized as follows: Section 2, we start with the introduction of augmented Solow model and show the dependence of economic growth on population growth, physical capital, and the core of this paper human capital. The bulk of this paper will focus on the empirical analysis of tertiary education. Estimation methods, such as Anderson-Hsiao estimator and Arellano-Bond GMM estimators, will be presented in Section 3. In Section 4, we introduce the dataset and our empirical model which includes different ISCED levels of tertiary education. Regression results from different estimation techniques will be reported in Section 5. Lastly, we conclude in Section 6 with a discussion of current U.S. tertiary education system, and how the results can potentially pose implications in growth policies.

2 Theoretical Background

In 1992, Mankiw, Romer, and Weil presented an augmented Solow model where human capital is implemented into the standard Solow model. They found this critical reappraisal fit the economic growth data extremely well. In this section, we briefly review the augmented Solow model and discuss the implications for the effect of tertiary education on economic growth.

The augmented Solow model incorporates the human capital into the original model. The production function is assumed to be Cobb-Douglas as the following:

$$Y_t = K_t^{\alpha} H_t^{\phi} (A_t L_t)^{1-\alpha-\phi} \tag{2.1}$$

$$\alpha, \phi \in [0,1], \alpha + \phi \in [0,1]$$

where Y, K, H, L, A, t denote output, physical capital, human capital, labor, level of technology and time, respectively. α and ϕ are constants. The original Solow model is just a special case of (2.1) with $\phi = 0$.

So the augmented Solow growth model exhibits constant returns to scale in its three factors: physical capital K_t, human capital H_t and effective units of labor $A_t L_t$. We further define $k_t = K_t / A_t L_t$ as the stock of physical capital per effective unit of labor, $h_t = H_t / A_t L_t$ as the stock of human capital per effective unit of labor, and $y_t = Y_t / A_t L_t$ as the output per effective unit of labor. Therefore, the production function (2.1) becomes:

$$y_t = k_t^{\alpha} h_t^{\phi} \tag{2.2}$$

Taking natural logs of both sides we have,

$$ln(y_t) = \alpha ln(k_t) + \phi ln(h_t) \tag{2.3}$$

Differentiate (2.3) with respect to time t,

$$\frac{\dot{y}_t}{y_t} = \alpha\frac{\dot{k}_t}{k_t} + \phi\frac{\dot{h}_t}{h_t} \tag{2.4}$$

where $\dot{y}_t = \frac{dy_t}{dt}$, $\dot{k}_t = \frac{dk_t}{dt}$ and $\dot{h}_t = \frac{dh_t}{dt}$.

To find how the dynamic economy works. we further assume that the evolution of K_t and H_t is governed by the law of motion:

$$\dot{K}_t = s_K Y_t - \delta K_t \tag{2.5}$$

$$\dot{H}_t = s_H Y_t - \delta H_t \tag{2.6}$$

where s_K and s_H are the fractions of output invested in the production, respectively. δ is the depreciation rate of physical capital and human capital.

We also assume that labor and level of technology grow exogenously at rates n and g that is:

$$\dot{L}_t = nL_t \tag{2.7}$$

$$\dot{A}_t = gA_t \tag{2.8}$$

Note $k_t = K_t/A_tL_t$ and differentiate it with respect to time t,

$$\begin{aligned}\dot{k}_t &= \frac{\dot{K}_t}{A_tL_t} - \frac{K_t}{[A_tL_t]^2}[\dot{A}_tL_t + A_t\dot{L}_t] \\ &= s_K y - (n+g+\delta)k \end{aligned} \tag{2.9}$$

Similarly, we have

$$\dot{h}_t = s_H y - (n+g+\delta)h \tag{2.10}$$

At steady state, $\dot{k} = \dot{h} = 0$ which implies,

$$y = \frac{(n+g+\delta)}{s_K}k = \frac{(n+g+\delta)}{s_H}h \tag{2.11}$$

With (2.2), the steady state k^* and h^* are given by,

$$k^* = \left(\frac{s_K^{1-\phi}s_H^{\phi}}{n+g+\delta}\right)^{\frac{1}{1-\alpha-\phi}} \tag{2.12}$$

$$h^* = \left(\frac{s_K^{\alpha}s_H^{1-\alpha}}{n+g+\delta}\right)^{\frac{1}{1-\alpha-\phi}} \tag{2.13}$$

Substitute k^* and h^* into the production function (2.2), multiply both sides by A_t then take logs, we finally get,

$$ln\left(\frac{Y_t}{L_t}\right) = ln(A_t) + gt - \frac{\alpha+\phi}{1-\alpha-\phi}ln(n+g+\delta) + \frac{\alpha}{1-\alpha-\phi}ln(s_K) + \frac{\phi}{1-\alpha-\phi}ln(s_H)$$

or equivalently,

$$ln\left(\frac{Y_t}{L_t}\right) = ln(A_t) + gt - \frac{\alpha}{1-\alpha}ln(n+g+\delta) + \frac{\alpha}{1-\alpha}ln(s_K) + \frac{\phi}{1-\alpha}ln(h_t^*) \tag{2.14}$$

The reduced form equation (2.14) shows how economic growth depends on population growth rate, accumulation of physical capital and the level of human capital. As the sign of $ln(h_t^*)$ in the equation is positive, one should expect that human capital has a positive effect on economic growth. The result of the augmented Solow model serves as the theoretical ground in the following empirical analysis.

Although human capital has many dimensions, in this paper I assume human capital is directly related to education participation and completion. The main interest of the study is to measure the effects of different levels in tertiary education on economic growth. However, I also include the secondary education since it is well known that secondary education has positive effects on economic growth and the level of tertiary education is positively related to the level of secondary education. Therefore, omitting secondary education will bias the coefficients on tertiary education variables.

3 Estimation Methods

For most of the time, we need to deal with omitted variable bias and reversal causality when we analyze the panel data. It is very common to include lagged dependent variable as an independent variable into macroeconomics regression. However, this would cause substantial bias if we do not pay enough attention as Nickell (1981) claims. His paper shows the common way of demeaning process which subtracts the individual means of dependent variable and each independent variable from the respective variables can introduce correlations between regressors and errors.

Suppose we have the following dynamic fixed effects model,

$$y_{i,t} = \delta y_{i,t-1} + x'_{i,t}\beta + \mu_i + \epsilon_{i,t} \tag{3.15}$$

$$\epsilon_{i,t} \sim N(0, \sigma^2_\epsilon)$$

$$E[\epsilon_{i,t}, \epsilon_{j,s}] = 0, i \neq j \ or \ t \neq s$$

$$E[\epsilon_{i,t}, \mu_i] = 0 \ \forall i, t$$

$$E[\epsilon_{i,t}, x_{i,t}] = 0 \ \forall i, t$$

where $y_{i,t}$ is the dependent variable, $y_{i,t-1}$ is the one period lagged dependent variable, δ is a scalar, μ_i is the fixed-effect variable, $x_{i,t}$ is a $k \times 1$ vector of regressors, β is a $k \times 1$ vector of parameters and $\epsilon_{i,t}$ is an idiosyncratic error.

The above equation (3.1) contains a lagged dependent variable to better specify the dynamic feature of the model. To get rid of the unobserved heterogeneity, you first difference Equation (3.1) to obtain,

$$y_{i,t} - y_{i,t-1} = \delta(y_{i,t-1} - y_{i,t-2}) + (x_{i,t} - x_{i,t-1})'\beta + \epsilon_{i,t} - \epsilon_{i,t-1} \tag{3.16}$$

or equivalently,

$$\Delta y_{i,t} = \delta\Delta y_{i,t-1} + \Delta x'_{i,t}\beta + \Delta\epsilon_{i,t} \tag{3.17}$$

The fixed effects μ_i is removed in the differenced Equation (3.3), however, now we have a correlation between independent variables $\Delta y_{i,t-1}$ and $\Delta\epsilon_{i,t}$ since the former one contains $y_{i,t-1}$ and the latter contains $\epsilon_{i,t-1}$. Thus, the usual approach to estimate the fixed-effect model, least squares dummy variable estimator (LSDV), is no longer appropriate to generate unbiased estimates.

Anderson and Hsiao (1981) propose instrumenting for $\Delta y_{i,t-1}$ with $y_{i,t-2}$ or $(y_{i,t-2} - y_{i,t-3})$ which are uncorrelated with $\Delta\epsilon_{i,t}$ but correlated with $\Delta y_{i,t-1}$. Arellano and Bond (1991) show that using the lagged differences as instruments will generally give larger variance than using lagged levels. Therefore, we use lagged levels of $y_{i,t}$ as instruments here. Suppose we have a dimension N by T panel, the Anderson-Hsiao estimator is given by

$$\widehat{\rho}_{AH} = (Z'X)^{-1}Z'Y \tag{3.18}$$

where

$$Z = \begin{bmatrix} \begin{bmatrix} y_{1,1} & \Delta x'_{1,3} \\ \vdots & \vdots \\ y_{1,T-2} & \Delta x'_{1,T} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} y_{N,1} & \Delta x'_{N,3} \\ \vdots & \vdots \\ y_{N,T-2} & \Delta x'_{N,T} \end{bmatrix} \end{bmatrix}_{N(T-2)\times(k+1)} \qquad X = \begin{bmatrix} \begin{bmatrix} \Delta y_{1,2} & \Delta x'_{1,3} \\ \vdots & \vdots \\ \Delta y_{1,T-1} & \Delta x'_{1,T} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} \Delta y_{N,2} & \Delta x'_{N,3} \\ \vdots & \vdots \\ \Delta y_{N,T-1} & \Delta x'_{N,T} \end{bmatrix} \end{bmatrix}_{N(T-2)\times(k+1)}$$

$$Y = \begin{bmatrix} \Delta y_{1,3} \\ \vdots \\ \Delta y_{1,T} \\ \vdots \\ \Delta y_{N,3} \\ \vdots \\ \Delta y_{N,T} \end{bmatrix}_{N(T-2)\times 1}$$

Anderson-Hsiao estimator is essentially an IV estimator using lagged levels of dependent variable as instruments to solve the non-orthogonal issue between differenced regressor and differenced error term in the dynamic panel data model.

Although Anderson-Hsiao estimator is widely used, a more efficient estimator is suggested by Arellano and Bond (1991). Arellano and Bond set up a system of generalized method of moments (GMM) equations to exploit more information from the data. They use the orthogonality restrictions on moment conditions between lagged levels of $y_{i,t}$ and the error term to get additional instruments in order to gain more efficiency. For example, in Equation (3.3), for $t = 3$, $y_{i,1}$ is a valid instrument for $\Delta y_{i,2}$; for $t = 4$, $y_{i,1}$ and $y_{i,2}$ are valid instruments for $\Delta y_{i,3}$; so on and so forth. Therefore, we get an additional instrument for each subsequent t and the instruments set for $\Delta y_{i,T-1}$ is $(y_{i,1}, y_{i,2}, ..., y_{i,T-2})$. Coupled with other lagged levels of the regressors, those instruments construct a block-diagonal matrix Z_i^* whose sth block is given by $diag(y_{i,1}...y_{i,s}x_{i,1}...x_{i,s+1})$ for $s = 1, ..., T-2$. And $Z^* = (Z_1^{*'}, ..., Z_N^{*'})'$. More specifically,

$$Z_i^* = \begin{bmatrix} \begin{bmatrix} y_{i,1} & x'_{i,1} & x'_{i,2} \end{bmatrix} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \begin{bmatrix} y_{i,1} & \cdots & y_{i,T-2} & x'_{i,1} & \cdots & x'_{i,T-1} \end{bmatrix} \end{bmatrix}_{(T-2)\times T(T-2)}$$

Given the moment conditions $E[Z_i^{*'}\Delta\epsilon_i] = 0, i = 1, ..., N$, the Arellano and Bond GMM estimator is given by

$$\widehat{\rho}_{AB} = (X'Z^*A_N Z^{*'}X)^{-1}X'Z^*A_N Z^{*'}Y$$

where X and Y are defined the same as above, $A_N = (\frac{1}{N}\sum_i^N Z_i^{*'}BZ_i^*)^{-1}$ and B is a $(T-2)\times(T-2)$ square matrix with twos in the main diagonals, minus one in the first subdiagonals, and zeros otherwise. This estimator is usually referred as one-step GMM estimator[3].

[3] Arellano and Bond also provide another estimator which is called two-step GMM estimator. Although asymptotically more efficient, the two-step estimator tend to be severely downward biased. See Blundell and Bond (1998).

Sometimes the lagged levels of regressors are not good instruments for the first-differenced regressors. The estimator becomes less informative when δ increases to unity. Arellano and Bover (1995) and Blundell and Bond (1998) revealed the potential weakness of the original GMM estimator and proposed an augmented version in their work. The original GMM estimator is often referred as difference GMM estimator and the augmented one is called system GMM estimator. The system GMM estimator uses the first-differenced equation and the level equation to build a system of two equations,

$$\begin{bmatrix} \Delta y_{i,t} \\ y_{i,t} \end{bmatrix} = \delta \begin{bmatrix} \Delta y_{i,t-1} \\ y_{i,t-1} \end{bmatrix} + \begin{bmatrix} \Delta x'_{i,t} \\ x'_{i,t} \end{bmatrix} \beta + \begin{bmatrix} \Delta \epsilon_{i,t} \\ \mu_i + \epsilon_{i,t} \end{bmatrix} \tag{3.19}$$

or equivalently,

$$\Delta y^{+}_{i,t} = \delta \Delta y^{+}_{i,t-1} + \Delta x^{+'}_{i,t} \beta + \Delta \epsilon^{+}_{i,t} \tag{3.20}$$

with the matrix of instruments,

$$Z^{+}_{i} = \begin{bmatrix} Z^{*}_{i} & 0 \\ 0 & \Delta Z^{*}_{i} \end{bmatrix} \tag{3.21}$$

where Z^{*}_{i} is the same as defined above and ΔZ^{*}_{i} is a block-diagonal matrix whose sth block is given by $diag(\Delta y_{i,1}...\Delta y_{i,s} \Delta x_{i,1}...\Delta x_{i,s+1})$ for $s = 1, ..., T-2$. And $Z^{+} = (Z^{+'}_{1}, ..., Z^{+'}_{N})'$. Given the moment conditions $E[Z^{+'}_{i} \Delta \epsilon^{+}_{i}] = 0$, the system GMM estimator is given by

$$\widehat{\rho}_{SysGMM} = (X^{+'} Z^{+} A^{+}_{N} Z^{+'} X^{+})^{-1} X^{+'} Z^{+} A^{+}_{N} Z^{+'} Y^{+}$$

where

$$X^+ = \begin{bmatrix} \begin{bmatrix} \Delta y^+_{1,2} & \Delta x^{+'}_{1,3} \\ \vdots & \vdots \\ \Delta y^+_{1,T-1} & \Delta x^{+'}_{1,T} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} \Delta y^+_{N,2} & \Delta x^{+'}_{N,3} \\ \vdots & \vdots \\ \Delta y^+_{N,T-1} & \Delta x^{+'}_{N,T} \end{bmatrix} \end{bmatrix}_{2N(T-2)\times(k+1)} \qquad Y^+ = \begin{bmatrix} \Delta y^+_{1,3} \\ \vdots \\ \Delta y^+_{1,T} \\ \vdots \\ \Delta y^+_{N,3} \\ \vdots \\ \Delta y^+_{N,T} \end{bmatrix}_{2N(T-2)\times 1}$$

and $A^+_N = (\frac{1}{N}\sum_i^N Z_i^{+'} B^+ Z_i^+)^{-1}$ and B^+ is a $2(T-2) \times 2(T-2)$ square matrix with twos in the main diagonals, minus one in the first sub-diagonals, and zeros otherwise.

Arellano and Bond's system GMM estimator is designed for small T large N panel data which is the case of the dataset used in this paper. Their estimator optimally exploits all the linear moment restrictions that follow from the assumption of no serial correlation in the errors of an equation which contains individual effects, lagged dependent variables and no strictly exogenous variables. However, the instrument variables constructed from the real world data could be invalid instruments. For example, in this paper we use lagged levels and differences of dependent variables (GDP per capita) as instruments. These instruments could be invalid in two scenarios: 1) they are weakly correlated with the endogenous explanatory variable. Although we find strong correlation between GDP per capita in current year and past year in most countries, lagged levels of GDP per capita could be poor instruments in some Sub-Saharan African countries. GDP in countries like Angola and Nigeria are largely influenced by commodity price such as oil and metals. Strong price fluctuations are very likely to shutdown the relevance of GDP per capita in past years and invalidate the instruments; 2) they directly affect the dependent variable. If the instruments are correlated with the error term, they do not satisfy the orthogonality conditions. It is possible that for some countries GDP per capita in current year is not only correlated with its one-period lag but also correlated with its two-period lag or three. Using lagged GDP per capita as instruments for countries with strong persistence (current value is affected by values in the far past) in GDP will most likely bias the results from system GMM because that will invalidate the instruments given the short time period in our data.

4 Empirical Model and Data

4.1 Model Specification

In order to decompose the impacts of tertiary education at individual level, I divide the tertiary education into three levels defined by International Standard Classification of Education (ISCED). Country fixed effect is included to overcome the unobserved heterogeneity that is constant over time. I also take into account the year effect to catch the global macroeconomic shock.

The estimation model is set up as the following,

$$
\begin{aligned}
y_{i,t} = \beta_0 + \beta_1 y_{i,t-1} + \beta_2 T_{1i,t} + \beta_3 T_{2i,t} + \beta_4 T_{3i,t} + \beta_5 Sec_{i,t} + \beta_6 k_{i,t} \\
+ \beta_7 Trade_{i,t} + \beta_8 Tech_{i,t} + \mu_i + \pi_t + \epsilon_{i,t}
\end{aligned}
$$

where $y_{i,t}$ is real GDP per capita at time t in country i. $T_{1i,t}$ is number of tertiary ISCED level 5 graduates. $T_{2i,t}$ is number of tertiary ISCED level 6&7 graduates. $T_{3i,t}$ is number of tertiary ISCED level 8 graduates. $Sec_{i,t}$ is secondary education enrollment. $y_{i,t-1}$ is real GDP per capita with one period lag. $k_{i,t}$ is capital formation. $Trade_{i,t}$ is trade share measured by sum of imports and exports to GDP ratio. $Tech_{i,t}$ is technology progress which is the sum of population growth rate plus 0.05 following MRW. μ_i is country fixed effect. π_t is year effect. $\epsilon_{i,t}$ is the idiosyncratic error term.

4.2 Data Description

The paper uses a panel data of 77 countries over the 1998-2011 period. The dataset comprises 44 developing countries and 33 developed countries. I use annual data instead of 5-year average data in usual empirical research since the education data on tertiary education is limited. I do not have data for all the variables in all countries for all years, thus I have an unbalanced panel dataset for estimation. Real GDP per capita and technology progress data is collected from Penn World Table 8.1. Gross capital formation and trade share data is obtained from World Development Indicators. Educational data including the number of tertiary graduates and secondary enrollment ratio comes from United Nations Educational, Scientific and Cultural Organization (UNESCO). The dependent variable is real GDP per capita in natural logs measured in constant 2005 dollars. The explanatory variables are listed in Table 1.

Summary statistics of variables are presented in Table 2. Table 3 and Table 4 show the summary for developing countries and developed countries separately. All variables are in natural logs except technology level which contains negative values and capital formation and trade which are measured in percentage.

It is not surprising to see on average higher real GDP per capita in developed countries than in developing countries. Although average gross capital formation of developed counties is only slightly higher than that of developing countries, the standard deviation is smaller in developed countries showing less disparity in physical

Table 3.1: Description of explanatory variables

Variables	Description
lgdp	Real GDP per capita lagged one period.
k	Gross capital formation (% of GDP), consists of outlays on additions to the fixed assets of the economy plus net changes in the level of inventories.
trade	Trade, sum of exports and imports of goods and services measured as a share of gross domestic product.
li5	Number of graduates in ISCED level 5 tertiary education.
li67	Number of graduates in ISCED level 6&7 tertiary education.*
li8	Number of graduates in ISCED level 8 tertiary education.
tech	Technology progress which is the population growth rate plus 0.05 following MRW.
lser	Secondary enrolment ratio. It is the number of students enrolled in secondary education, regardless of age, expressed as a percentage of the official school-age population corresponding to the secondary education.

**Unfortunately, UNESCO did not collect ISCED level 6 and level 7 data separately. In addition, bachelor's and master's programs were not recorded until the Bologna process implementation in Europe and some other countries.*

capital. Secondary enrollment ratio is higher in developed countries as they have established a more comprehensive basic educational system. Developed countries have more graduates in ISCED level 6, 7 and 8 level tertiary education which compose the major part of tertiary education, while the number of graduates in ISCED level 5 education is bigger in developing countries. I also notice a higher technology progress rate in developing countries. Since the way we adopt the technology progress is based on MRW's work, higher population growth rate of developing countries included in the dataset is the reason why this happens.

Table 3.2: Descriptive statistics of the variables: all countries

Total VARIABLES	(1) N	(2) mean	(3) sd	(4) min	(5) max
k	792	23.91	5.62	10.44	58.15
trade	793	87.93	37.05	18.76	217.57
li5	734	9.23	2.02	4.03	13.46
li67	806	10.63	1.75	5.46	14.75
li8	747	6.57	2.25	0.00	11.20
tech	806	0.88	1.39	-2.80	17.67
lgdp	806	9.41	1.09	5.90	11.72
lser	746	4.47	0.35	2.38	5.08
Number of countries	77	77	77	77	77

Table 3.3: Descriptive statistics of the variables: developing countries

Developing Countries VARIABLES	(1) N	(2) mean	(3) sd	(4) min	(5) max
k	398	23.87	6.62	10.44	58.15
trade	399	86.11	34.70	21.85	217.57
li5	349	9.43	2.03	4.03	13.46
li67	412	10.41	1.79	5.46	14.20
li8	358	5.95	2.27	0.00	10.59
tech	412	1.34	1.66	-2.80	17.67
lgdp	412	8.77	1.12	5.90	11.72
lser	354	4.28	0.42	2.38	4.72
Number of countries	44	44	44	44	44

Table 3.4: Descriptive statistics of the variables: developed countries

Developed Countries VARIABLES	(6) N	(7) mean	(8) sd	(9) min	(10) max
k	394	23.94	4.38	11.97	41.65
trade	394	89.77	39.24	18.76	190.23
li5	385	9.05	2.00	4.03	13.23
li67	394	10.86	1.68	6.17	14.75
li8	389	7.14	2.08	0.00	11.20
tech	394	0.41	0.80	-2.21	2.94
lgdp	394	10.08	0.48	8.80	11.07
lser	392	4.64	0.13	4.38	5.08
Number of countries	33	33	33	33	33

5 Regression Analysis

I run pooled OLS, fixed-effects, Anderson-Hsiao, Difference GMM and System GMM on the above model. The presence of country fixed effect will cause the OLS generate biased estimates. To deal with this country specific effect, the fixed-effects estimator is introduced. Although the fixed effect is removed by demeaning the equation, due to the inclusion of lagged dependent variable, there is some endogeneity problem in the equation now. Anderson-Hsiao estimator is suitably applied in this circumstance. Arellano and Bond provide a more efficient estimator which is based on generalized method of moments. Later on, an augmented version, system GMM, is proposed by Arellano and Bover (1995) and Blundell and Bond (1998).

I first run regressions for all available countries in the data set. In Table 5, the coefficient of secondary enrollment ratio is insignificant in all models. A plausible explanation is that since we pooled all countries together regardless of their stages of economic development, the effect of secondary education is mixed: developed countries with well established secondary education system have low marginal rate of return while developing countries still have room for improvements. The coefficient of capital formation is positively significant in all models at 1% level. This confirms with the results from MRW model. Now we turn to three different levels of tertiary education. For ISCED level 5 education, the coefficient is significant at 1% level in system-GMM model which is 0.00849. The positive elasticity shows that 1% change in ISCED level 5 graduates will increase real GDP per capita by 0.00849%. Compared to the contribution of trade whose efficient is only 0.000705, ISCED level 5 education has more than 10 times effectiveness on the growth of real GDP per capita. However, ISCED level 6&7 and ISCED level 8 education do not show any significance in system GMM model. Again, the reason behind could be that the impacts of certain levels of tertiary education depends on the stage of a country's economic development. Therefore, I proceed to examine the impacts of different levels of tertiary education on the economic growth for developed countries and developing countries respectively.

Table 6 shows the regression results for developed countries. The coefficient of secondary education remains insignificant in all models. Since the system of secondary education is fully established in developed countries during the sample period, there is no significant gain on economic growth from additional investment in secondary education. The capital formation remains significant but larger coefficient for developed countries. Now we focus on the impacts of tertiary education. The coefficient of ISCED level 5 education is significant in Anderson-Hsiao, difference GMM and system GMM models. The coefficient is 0.0109 in the system GMM model which means each 1% increase in the ISCED level 5 graduates will yield 0.0109% increase in real GDP per capita. More importantly, the coefficients of ISCED level 6&7 and ISECED level 8 become significant for developed countries. The coefficient of ISCED level 6&7 is 0.0197 which is almost twice as that of ISCED level 5 which implies that the contribution of undergraduate and master education is higher than short-cycle tertiary education. The coefficient of ISCED level 8 education is 0.0107 which a little bit lower than that of ISCED level 5. This implies the doctoral education has almost the same effect as short-cycle tertiary education on economic growth.

Table 7 shows the results for developing countries. The coefficient of secondary education becomes significant in system GMM model which is 0.106. It is well known that secondary education plays a vital role in developing countries where there is big room to improve the quality of basic education. The coefficient of ISCED level 5 education also shows significance in system GMM model while ISCED level 6&7 and 8 are insignificant. One thing worth noting is that the coefficient of ISCED level 5 is much lower than that of secondary education in developing countries. The implication is that developing countries should invest more in secondary education than short-cycle tertiary education. Since tertiary education need stronger economy and larger knowledge base to support its multi-dimensional fields and complicated structures, developing countries should focus their development on secondary education.

Table 3.5: Determinants of economic growth: all countries

VARIABLES	(1) OLS	(2) FE	(3) AH	(4) Diff-GMM	(5) Sys-GMM
L.lgdp	0.990***	0.809***	0.947***	0.777***	0.974***
	(0.00341)	(0.0300)	(0.0838)	(0.0548)	(0.00906)
lser	0.0114	0.0355	0.0379	0.0526	0.0385
	(0.0133)	(0.0219)	(0.0453)	(0.0441)	(0.0437)
k	0.00206***	0.00441***	0.00441***	0.00553***	0.00418***
	(0.000328)	(0.000742)	(0.000920)	(0.000925)	(0.000644)
li5	0.00199	0.00451**	0.00539*	0.00558*	0.00849***
	(0.00121)	(0.00217)	(0.00307)	(0.00300)	(0.00327)
li67	0.00343	0.0191*	-0.00937	0.00390	0.00266
	(0.00270)	(0.0111)	(0.0179)	(0.0231)	(0.00960)
li8	-0.00360*	-0.00674*	-0.00132	-0.000679	0.00264
	(0.00209)	(0.00394)	(0.00430)	(0.00403)	(0.00419)
trade	0.000108**	0.000537**	0.000832***	0.000565**	0.000705***
	(5.26e-05)	(0.000240)	(0.000299)	(0.000243)	(0.000198)
tech	-0.00440**	-0.000149	0.00269	0.00337	0.00532
	(0.00187)	(0.00217)	(0.00270)	(0.0208)	(0.0143)
Constant	-0.00331	1.337***		1.643***	-0.161
	(0.0540)	(0.301)		(0.520)	(0.211)
Observations	548	548	456	456	548
R-squared	0.999	0.959			

*All two-tailed tests. Robust standard errors in parentheses. For simplicity, I omit to report year dummies. (*** p<0.01, ** p<0.05, * p<0.1)*

Table 3.6: Determinants of economic growth: developed countries

VARIABLES	(1) OLS	(2) FE	(3) AH	(4) Diff-GMM	(5) Sys-GMM
L.lgdp	0.984***	0.772***	0.897***	0.763***	0.936***
	(0.00636)	(0.0285)	(0.0580)	(0.0393)	(0.0293)
lser	-0.00509	0.0132	0.0281	0.0408	0.0717
	(0.0118)	(0.0215)	(0.0434)	(0.0424)	(0.0597)
k	0.00254***	0.00539***	0.00581***	0.00648***	0.00556***
	(0.000366)	(0.000809)	(0.00108)	(0.000821)	(0.000731)
li5	-0.000166	0.00345	0.00572**	0.00567**	0.0109***
	(0.00129)	(0.00206)	(0.00278)	(0.00241)	(0.00331)
li67	0.00525**	0.0316***	0.0250*	0.0367***	0.0197*
	(0.00251)	(0.0102)	(0.0143)	(0.0107)	(0.0119)
li8	-0.00229	-0.00588	0.000970	0.00231	0.0107*
	(0.00176)	(0.00593)	(0.00639)	(0.00670)	(0.00576)
trade	0.000156***	0.00133***	0.00162***	0.00155***	0.000851***
	(4.75e-05)	(0.000232)	(0.000272)	(0.000278)	(0.000262)
tech	-0.000417	0.000261	0.00416	0.00244	0.00738
	(0.00366)	(0.00352)	(0.00451)	(0.00426)	(0.00654)
Constant	0.117*	1.676***		1.457***	-0.244
	(0.0608)	(0.245)		(0.314)	(0.257)
Observations	333	333	289	289	333
R-squared	0.998	0.974			

*All two-tailed tests. Robust standard errors in parentheses. For simplicity, I omit to report year dummies. (*** p<0.01, ** p<0.05, * p<0.1)*

Table 3.7: Determinants of economic growth: developing countries

VARIABLES	(1) OLS	(2) FE	(3) AH	(4) Diff-GMM	(5) Sys-GMM
L.lgdp	0.995***	0.765***	0.842	0.666***	0.948***
	(0.00551)	(0.0728)	(0.741)	(0.104)	(0.0162)
lser	0.0334**	-0.00260	0.0243	0.0494	0.106*
	(0.0147)	(0.0384)	(0.0863)	(0.0490)	(0.0645)
k	0.00120***	0.00310**	0.00299*	0.00357**	0.00265**
	(0.000414)	(0.00118)	(0.00180)	(0.00142)	(0.00115)
li5	0.00529*	0.00286	0.0161	-0.000309	0.0245**
	(0.00286)	(0.00673)	(0.0180)	(0.00921)	(0.0122)
li67	-0.00479	-0.0230	-0.0492	-0.0541	-0.0164
	(0.00498)	(0.0272)	(0.0386)	(0.0342)	(0.0114)
li8	-0.000511	-0.00850*	-0.00427	-0.00257	-0.00105
	(0.00331)	(0.00465)	(0.00686)	(0.00557)	(0.00467)
trade	7.59e-05	-6.90e-05	-0.000152	-0.000323	9.70e-05
	(8.13e-05)	(0.000226)	(0.000533)	(0.000283)	(0.000235)
tech	-0.00424*	-0.00101	0.00739	0.0111*	0.00832
	(0.00246)	(0.00356)	(0.00855)	(0.00627)	(0.00548)
Constant	-0.0914	2.307***		3.259***	-0.0805
	(0.0545)	(0.801)		(1.057)	(0.307)
Observations	215	215	167	167	215
R-squared	0.999	0.955			

*All two-tailed tests. Robust standard errors in parentheses. For simplicity, I omit to report year dummies. (*** p<0.01, ** p<0.05, * p<0.1)*

These results raise questions about the emphasis of secondary education which was the main concentration by the governments in decades. The insignificance of secondary enrollment ratio on the GDP per capita in Table 5 and 6 seemingly implies that secondary education does not contribute much to the economic growth. One possible explanation is the fully saturated establishment of secondary education (the average secondary enrollment ratio in developed countries is 104.8%) that in most developed countries the marginal rate of return of secondary education is minimal. However, the secondary education shows its significant economic influence in developing countries where basic education supply and quality shortfall commonly exists (the average secondary enrollment ratio in developing countries is 77.5%). Therefore, it is clear that the marginal rate of return for secondary education depends on the country's stage of economic development. It would be wise for developing countries with limited resources to concentrate on secondary education which cost less than tertiary education but inefficient for developed countries to do the same.

If the effect of secondary education on economic growth depends on the stage of economic development, it is also true for the different levels of tertiary education. The above results show that short-cycle/pre-college education is growth enhancing in both developed and developing countries while undergraduate and graduate education are effective in increasing GDP per capita only in developed countries. As the first level of tertiary education, the short-cycle/pre-college education is typically designed to be practically based to prepare students to enter the labor market. Even in most developed countries such as the United States, Japan or Germany, workers with occupationally specific knowledge are in great demand to support economic development by quickly responding to the needs of industry. The employment-oriented objective of short-cycle/pre-college education is self-explanatory in reducing unemployment rate of students and enhancing economic growth in both developed and developing countries.

On the other hand, undergraduate and graduate college education only show positive effects on economic growth in developed countries. The possible reasons behind this can be multifold. Firstly, the cost of tertiary education is undeniably higher than other types of education. In developing countries, unit cost of tertiary education relative to other levels is two to three times higher than that in OECD countries.[4] It is very natural for governments with constrained budgets to cut short the investment in tertiary education. The lack of financial support inevitably decreases the quality of education, and therefore its marginal rate of return. Secondly, underdeveloped areas may not have necessary mechanisms and markets to absorb the graduates from tertiary education. Without proper economic capacities, highly skilled labor could be underutilized. Thirdly, knowledge generates knowledge. Investment in tertiary education is less fruitful if the country has a poor baseline in intellectual culture. A substantial mass of qualified teachers and researchers is usually the prerequisite condition for tertiary education to thrive and significantly affect economic development. Lastly, developing countries often suffer from the brain drain problem. The process of globalization further worsens the situation by attracting the best and brightest students to the wealthier countries. These together explain why higher levels of tertiary education are weighed down in developing countries.

Developed countries ought to allocate more resources into tertiary education because it is designed to promote the production of knowledge and generate innovations which are the key factors in economic growth. Giving up tertiary education and leaving it to the private institutions would undermine its quality and link it with unstable market risks which can significantly hinder the economic development of developed countries in the long term.

5.1 Arellano-Bond Test for Serial Correlation

The moment conditions used by system GMM are only valid if idiosyncratic errors exhibit no serial correlation at higher orders. The Arellano-Bond (AB) test can be conducted to test the serial correlation in the first-differenced errors. The null

[4] "Constructing Knowledge Societies: New Challenge for Tertiary Education", The World Bank.

hypothesis in AB test is no serial correlation. As shown in the table below, although the test rejects the null at order one in all countries and developed countries case, it does not imply the the model is misspecified because the first-differenced errors are most likely to be correlated when lagged dependent variable enters as an explanatory variable. However, we need the first-differenced errors to be uncorrelated at order two to validate the moment conditions and, indeed, for order two we cannot reject the null hypothesis at standard significance levels for any case which indicates no serial correlation is presented in the idiosyncratic errors.

Table 3.8: AB tests for serial correlation

	All countries		Developed countries		Developing countries	
Order	z	Prob > z	z	Prob > z	z	Prob > z
1	-2.8763	0.0040	-2.8898	0.0039	-1.48	0.1389
2	-1.3285	0.1840	-.85183	0.3943	-.95011	0.3421

H_0: no serial correlation

5.2 Invalid Instruments

Arellano and Bond's system GMM estimator is designed for small T large N panel data which is the case of the dataset used in this paper. Their estimator optimally exploits all the linear moment restrictions that follow from the assumption of no serial correlation in the errors of an equation which contains individual effects, lagged dependent variables and no strictly exogenous variables. However, the instrument variables constructed from the real world data could be invalid instruments. For example, in this paper we use lagged levels and differences of dependent variables (GDP per capita) as instruments. These instruments could be invalid in two scenarios: 1) They are weakly correlated with the endogenous explanatory variable. Although we find strong correlation between GDP per capita in current year and past year in most countries, lagged levels of GDP per capita could be poor instruments in some Sub-Saharan African countries. GDP in countries like Angola and Nigeria are largely influenced by commodity price such as oil and metals. Strong price fluctuations are very likely to shutdown the relevance of GDP per capita in past years and invalidate the instruments; 2) They directly affect the dependent variable. If the instruments are correlated with the error term, they do not satisfy the orthogonality conditions. It is possible that for some countries GDP per capita two or three years ago still contains additional information on its current year level even though we control for its one-period lag. Using lagged GDP per capita as instruments for countries with strong persistence (current value is affected by values in the far past) in GDP will most likely bias the results from system GMM because that will invalidate the instruments given the short time period in our data.

6 Conclusion

In this paper, I have examined the relation between each level of tertiary education and the economic growth of developed and developing countries. Previous literature has largely focused on the aggregate effect of tertiary education while its impact on economic growth is controversial (Hall and Jones, 1999; Reis and Sequeira, 2007; Busikova, 2013). As the development of tertiary education, researchers are attempting to investigate its macroeconomic and microeconomic impacts from different perspectives, such as tertiary education investment on state economic growth (Storm and Feiock, 1999) and founder's human capital on firm's performance (Colombo and Grilli, 2005). Composition of education stock plays an important role in shaping the incentives for investment in education (Ramcharan, 2004). Interpreting the specific impact of different levels of tertiary education, which usually requires large amount of monetary cost and human capital, can avoid wasteful investment and lead the country out of the knowledge trap, especially for those countries with limited access to educational resources.

Inspired by Mankiw, Romer and Weil's critical reappraisal of implementing human capital into Solow's pioneer work, I investigate the effects of different ISCED levels of tertiary education on economic growth of 77 countries over the period 1998-2011 and employ the System GMM method to overcome the potential biases in dynamic panel data estimation. The empirical results suggests that,

1) Secondary education has impacts on developing countries' economic growth while no significant effect is observed in developed countries where secondary education is well established.

2) Short-cycle or pre-college education makes contributions to economic growth in both developing and developed countries. Furthermore, the impact of short-cycle education in developing countries is more than twice as effective as in developed countries.

3) Bachelor's and Master's education show greater impacts on economic growth than other levels of tertiary education in developed countries, but it has insignificant impact in developing countries.

4) Doctoral education is positively related to developed countries' economic growth but insignificant in developing countries where education resources are often limited, such as funding issues and faculty shortages.

Disaggregating and inspecting tertiary education at different levels reveals the differential marginal effects of tertiary education and provides better guidance to policy makers on allocating resources efficiently since it can indicate as to which level of tertiary education should be emphasized in education policy formation. Developing countries facing potential "brain drain" and "knowledge trap" should consider directing more attraction in development of short-cycle education and attracting experts of emigrants as well as professionals from developed countries to make effort in developing basic tertiary educational system. Developed countries should keep investing in all types of tertiary education as each of them contributes to the economics growth. Missing out on providing support at the top will hinder the development of the best human capital and lose the attraction to entrepreneurs and innovators. Investing too little at the bottom of tertiary education is profoundly antithetical to the fundamental characteristic of education that education is cumulative after all.

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APPENDIX A

EDUCATION, TECHNOLOGY, HUMAN CAPITAL COMPOSITION AND ECONOMIC DEVELOPMENT

A.1 Educational Subsidy in GE

In section 2, we get the cutoff ability level between unskilled workers and generalists $X^*_{u,g}$ which is obtained by maximizing consumption of both sides. This implies

$$\arg\max_{X_{u,g}} TC^{ge}_t = X^*_{u,g}$$

Therefore, the total consumption at the equilibrium is

$$TC^{ge*}_t = \delta\left(A_{t-1} + \frac{2^{\frac{1-\alpha}{\alpha}} A^{\theta_G}_{t-1}}{1+\beta_G}(1 - X^{*1+\beta_G}_{u,g})\right) - (1 - X^*_{u,g})E \tag{A-1}$$

First order condition with respective to E gives us

$$\begin{aligned}\frac{dTC^{ge*}_t}{dE} &= \frac{\partial TC^{ge*}_t}{\partial E} + \underbrace{\frac{\partial TC^{ge*}_t}{\partial X^*_{u,g}}\frac{\partial X^*_{u,g}}{\partial E}}_{=0 \text{ since } TC^{ge*}_t \text{ is maximized at } X^*_{u,g}} \\ &= X^*_{u,g} - 1\end{aligned}$$

Since in GE $X^*_{u,g} < 1$, we have $\frac{dTC^{ge*}_t}{dE} < 0$ which implies an increase in the fraction of generalists caused by lower education cost will increase total consumption.

And at the equilibrium the growth rate can be presented as

$$\begin{aligned} r^{ge*}_{A,t} &= \frac{2^{\frac{1-\alpha}{\alpha}} A^{\theta_G - 1}_{t-1}}{1+\beta_G}(1 - X^{*1+\beta_G}_{u,g}) \\ &= \frac{2^{\frac{1-\alpha}{\alpha}} A^{\theta_G - 1}_{t-1}}{1+\beta_G}[1 - \left(\frac{E}{2^{\frac{1-\alpha}{\alpha}} \delta A^{\theta_G}_{t-1}}\right)^{\frac{1+\beta_G}{\beta_G}}] \end{aligned} \quad \text{(A-2)}$$

It is obvious that $\frac{\partial r^{ge*}_{A,t}}{\partial E} < 0$ which directly suggests an educational subsidy to decrease education cost in order to have higher growth rate.

A.2 Comparative Statics in ME

The total consumption is

$$TC^{me}_t = \int_0^{X_{u,s}} \delta A^U_{i,t} dX_i + \int_{X_{u,s}}^{X_{g,s}} (\delta A^S_{i,t} - E) dX_i + \int_{X_{g,s}}^{1} (\delta A^G_{i,t} - E) dX_i \quad \text{(A-3)}$$

Since $\underset{\{X_{u,s}, X_{g,s}\}}{\arg\max}\ TC^{me}_t = \{X^*_{u,s}, X^*_{g,s}\}$, the total consumption at the equilibrium is

$$\begin{aligned} TC^{me*}_t = \delta \left(A_{t-1} + \frac{2^{\frac{1}{\alpha}} c^{-1} A^{\theta_S}_{t-1}}{1+\beta_S} (X^{*1+\beta_S}_{g,s} - X^{*1+\beta_S}_{u,s}) + \frac{2^{\frac{1-\alpha}{\alpha}} A^{\theta_G}_{t-1}}{1+\beta_G} (1 - X^{*1+\beta_G}_{g,s}) \right) \\ -(1 - X^*_{u,s})E \end{aligned} \quad \text{(A-4)}$$

It is a little bit more complicated to understand the composition effect in ME than in GE as now we have two variables identifying the composition of human capital, $X^*_{u,s}$ and $X^*_{g,s}$. Therefore, we should examine the effect in three cases: both $X^*_{u,s}$ and $X^*_{g,s}$

changes; $X^*_{g,s}$ holds while $X^*_{u,s}$ changes; $X^*_{u,s}$ holds while $X^*_{g,s}$ changes. If we inspect the equations of $X^*_{u,s}$ and $X^*_{g,s}$, change in c^{-1} provokes the first case, change in E provokes the second and change in θ_G provokes the third.

Thus, we have

$$\begin{aligned}\frac{dTC_t^{me*}}{dc^{-1}} &= \frac{\partial TC_t^{me*}}{\partial c^{-1}} + \frac{\partial TC_t^{me*}}{\partial X^*_{u,s}}\frac{\partial X^*_{u,s}}{\partial c^{-1}} + \frac{\partial TC_t^{me*}}{\partial X^*_{g,s}}\frac{\partial X^*_{g,s}}{\partial c^{-1}} \\ &= \frac{2^{\frac{1}{\alpha}}\delta A_{t-1}^{\theta_S}}{1+\beta_S}(X_{g,s}^{*1+\beta_S} - X_{u,s}^{*1+\beta_S})\end{aligned}$$

Note in ME, $X^*_{g,s} > X^*_{u,s}$ so that $\frac{dTC_t^{me*}}{dc^{-1}} > 0$. This relationship shows the total consumption will rise if there is an increase in the fraction of specialists and a decrease in the fraction of generalists in ME.

Next, we have

$$\begin{aligned}\frac{dTC_t^{me*}}{dE} &= \frac{\partial TC_t^{me*}}{\partial E} + \frac{\partial TC_t^{me*}}{\partial X^*_{u,s}}\frac{\partial X^*_{u,s}}{\partial E} + \frac{\partial TC_t^{me*}}{\partial X^*_{g,s}}\frac{\partial X^*_{g,s}}{\partial E} \\ &= X^*_{u,s} - 1\end{aligned}$$

Obviously $\frac{dTC_t^{me*}}{dE} < 0$, this implies that holding the fraction of generalists constant, the total consumption increases if the fraction of specialists increases.

Last, we examine

$$\begin{aligned}\frac{dTC_t^{me*}}{d\theta_G} &= \frac{\partial TC_t^{me*}}{\partial \theta_G} + \frac{\partial TC_t^{me*}}{\partial X^*_{u,s}}\frac{\partial X^*_{u,s}}{\partial \theta_G} + \frac{\partial TC_t^{me*}}{\partial X^*_{g,s}}\frac{\partial X^*_{g,s}}{\partial \theta_G} \\ &= \frac{2^{\frac{1-\alpha}{\alpha}}\delta ln(A_{t-1})A_{t-1}^{\theta_G}(1 - X_{g,s}^{*1+\beta_G})}{1+\beta_G}\end{aligned}$$

Since $0 < X^*_{g,s} < 1$ and $A_{t-1} > 1$ which implies $\frac{dTC_t^{me*}}{d\theta} > 0$. This shows if we hold the fraction of unskilled workers constant, larger fraction of generalists induced by an increase in the intertemporal technology effect θ_G will increase the total consumption in ME.

Since

$$\begin{aligned}\frac{dr_{A,t}^{me*}}{dc^{-1}} &= \frac{\partial r_{A,t}^{me*}}{\partial c^{-1}} + \frac{\partial r_{A,t}^{me*}}{\partial X_{u,s}^*}\frac{\partial X_{u,s}^*}{\partial c^{-1}} + \frac{\partial r_{A,t}^{me*}}{\partial X_{g,s}^*}\frac{\partial X_{g,s}^*}{\partial c^{-1}} \\ &= 2^{\frac{1}{\alpha}} A_{t-1}^{\theta_S-1}\left[\frac{1}{1+\beta_S}(X_{g,s}^{*1+\beta_S} - X_{u,s}^{*1+\beta_S}) + \left(\frac{E}{2^{\frac{1}{\alpha}}c^{-1}\delta A_{t-1}^{\theta_S}}\right)^{\frac{1}{\beta_S}}\frac{X_{u,s}^{*\beta_S}}{\beta_S}\right. \\ &\left. + \frac{2c^{-1}A_{t-1}^{\theta_S-\theta_G}X_{g,s}^{*\beta_S} - X_{g,s}^{*\beta_G}}{\beta_G-\beta_S}(2c^{-1}A_{t-1}^{\theta_S-\theta_G})^{\frac{1}{\beta_G-\beta_S}-1}\right]\end{aligned}$$

plug in the values of $X_{u,s}^*$ and $X_{g,s}^*$, we observe $\frac{dr_{A,t}^{me*}}{dc^{-1}} > 0$ which implies lower coordination cost will increase the growth rate.

Following the same way, we find the effect of education cost on growth rate is

$$\begin{aligned}\frac{dr_{A,t}^{me*}}{dE} &= \frac{\partial r_{A,t}^{me*}}{\partial E} + \frac{\partial r_{A,t}^{me*}}{\partial X_{u,s}^*}\frac{\partial X_{u,s}^*}{\partial E} + \frac{\partial r_{A,t}^{me*}}{\partial X_{g,s}^*}\frac{\partial X_{g,s}^*}{\partial E} \\ &= -\frac{X_{u,s}^{*\beta_S}}{\beta_S\delta A_{t-1}}\left(\frac{E}{2^{\frac{1}{\alpha}}c^{-1}\delta A_{t-1}^{\theta_S}}\right)^{\frac{1}{\beta_S}-1}\end{aligned}$$

so $\frac{dr_{A,t}^{me*}}{dE} < 0$ gives the same implication as in GE. Lowering education cost will make it more affordable for unskilled workers to take education and therefore increase the participation rate in innovation in ME.

And we also have

$$\begin{aligned}\frac{dr_{A,t}^{me*}}{d\theta_G} &= \frac{\partial r_{A,t}^{me*}}{\partial \theta_G} + \frac{\partial r_{A,t}^{me*}}{\partial X_{u,s}^*}\frac{\partial X_{u,s}^*}{\partial \theta_G} + \frac{\partial r_{A,t}^{me*}}{\partial X_{g,s}^*}\frac{\partial X_{g,s}^*}{\partial \theta_G} \\ &= \frac{2^{\frac{1-\alpha}{\alpha}}ln(A_{t-1})A_{t-1}^{\theta_G-1}(1-X_{g,s}^{*1+\beta_G})}{1+\beta_G}\end{aligned}$$

Thus, $\frac{dr^{me*}_{A,t}}{d\theta_G} > 0$ which implies, in ME, if we do not change the ratio of unskilled workers to skilled workers, more generalists in the equilibrium will increase the growth rate.

A.3 Slopes of Technology Growth Rate

To draw a continuous curve over GE, ME and SE, we need to compare the slopes of the growth rate at the conjunctions t_1 and t_2.

If we totally differentiate r^{ge}, r^{me} and r^{se} w.r.t. A,

$$\frac{dr^{ge}}{dA} = \frac{\partial r^{ge}}{\partial A} + \frac{\partial r^{ge}}{\partial X_{ug}}\frac{\partial X_{ug}}{\partial A} \tag{A-5}$$

$$\frac{dr^{me}}{dA} = \frac{\partial r^{me}}{\partial A} + \frac{\partial r^{me}}{\partial X_{us}}\frac{\partial X_{us}}{\partial A} + \frac{\partial r^{me}}{\partial X_{gs}}\frac{\partial X_{gs}}{\partial A} \tag{A-6}$$

$$\frac{dr^{se}}{dA} = \frac{\partial r^{se}}{\partial A} + \frac{\partial r^{se}}{\partial X_{us}}\frac{\partial X_{us}}{\partial A} \tag{A-7}$$

Since in SE we restrict the value of $X_{gs} = 1$, this implies $\frac{\partial X_{gs}}{\partial A} = 0$. Now it does not hurt to add $\frac{\partial r^{se}}{\partial X_{gs}}\frac{\partial X_{gs}}{\partial A} = 0$ to the right hand side of (A-7) so that

$$\frac{dr^{se}}{dA} = \frac{\partial r^{se}}{\partial A} + \frac{\partial r^{se}}{\partial X_{us}}\frac{\partial X_{us}}{\partial A} + \frac{\partial r^{se}}{\partial X_{gs}}\frac{\partial X_{gs}}{\partial A} \tag{A-8}$$

Compare (A-6) and (A-8) at $t = t_2$ where $r_{me} = r_{se}$, they are exactly the same which implies the same slopes of r_{me} and r_{se} at t_2.

On the other hand, compare (A-5) to (A-6) at t_1 where $r_{ge} = r_{me}$. They are different in the function forms which implies the slopes are different at t_1.

APPENDIX B

MIGRATION EFFECTS ON HOME COUNTRY'S COMPOSITION OF HUMAN CAPITAL AND ECONOMIC DEVELOPMENT

B.1 Composition Effect and Brain Drain Effect

At the equilibrium where $X^*_{u,g} = \left[\frac{E - p\delta(A_f - A_h)}{2^{\frac{1-\alpha}{\alpha}}\delta A_h^{\theta}}\right]^{\frac{1}{\beta}}$, so

$$r^{ge}_{A,t} = \frac{2^{\frac{1-\alpha}{\alpha}} A^{\theta_G - 1}_{H,t-1}(1-p)(1 - X^{*1+\beta_G}_{u,g})}{(1+\beta_G)} - p(1 - X^*_{u,g}) \tag{B-1}$$

Therefore, the positive composition effect $C(p)$ and the negative brain drain effect $B(p)$ are

$$C(p) = \frac{2^{\frac{1-\alpha}{\alpha}} A^{\theta_G - 1}_{H,t-1}(1-p)(1 - X^{*1+\beta_G}_{u,g})}{(1+\beta_G)} \tag{B-2}$$

$$B(p) = p(1 - X^*_{u,g}) \tag{B-3}$$

To see whether the distance between $C(p)$ and $B(p)$ is expanding or shrinking after migration, we take the derivatives of both equation w.r.t. p and compare them at $p = 0$

$$C'(0) = \frac{2^{\frac{1-\alpha}{\alpha}} A_{H,t-1}^{\theta_G - 1}}{1+\beta_G}\left[\left(\frac{E}{2^{\frac{1-\alpha}{\alpha}}\delta A_{H,t-1}^{\theta_G}}\right)^{\frac{1+\beta_G}{\beta_G}} - 1\right] + \frac{A_{F,t-1} - A_{H,t-1}}{A_{H,t-1}\beta_G}\left(\frac{E}{2^{\frac{1-\alpha}{\alpha}}\delta A_{H,t-1}^{\theta_G}}\right)^{\frac{1}{\beta_G}} \tag{B-4}$$

$$B'(0) = 1 - \left(\frac{E}{2^{\frac{1-\alpha}{\alpha}}\delta A_{H,t-1}^{\theta}}\right)^{\frac{1}{\beta_G}} \tag{B-5}$$

Recall $X_{u,g}^{**} = \left(\frac{E}{2^{\frac{1-\alpha}{\alpha}}\delta A_{H,t-1}^{\theta}}\right)^{\frac{1}{\beta_G}}$, therefore

$$C'(0) = \frac{2^{\frac{1-\alpha}{\alpha}} A_{H,t-1}^{\theta_G - 1}}{1+\beta_G}(X_{u,g}^{**1+\beta_G} - 1) + \frac{A_{F,t-1} - A_{H,t-1}}{A_{H,t-1}\beta_G}X_{u,g}^{**} \tag{B-6}$$

$$B'(0) = 1 - X_{u,g}^{**} \tag{B-7}$$

If $C'(0) > B'(0)$, the distance is expanding which implies the growth rate is increasing, solve for $X_{u,g}^{**}$

$$X_{u,g}^{**} > \frac{A_{H,t-1}\delta\beta_G(1 + \beta_G + 2^{\frac{1-\alpha}{\alpha}} A_{H,t-1}^{\theta_G - 1})}{E\beta_G + (1+\beta_G)(A_{F,t-1} - A_{H,t-1})\delta + (1+\beta_G)A_{H,t-1}\delta\beta_G} \tag{B-8}$$

Since $C(0) > 0$ and $C(1) = 0$, $C'(0) > B'(0) > 0$ implies there must exist a $p^* \in (0, 1)$ maximizing $C(p) - B(p)$.

B.2 Thresholds for Beneficial Migration in ME and SE

For ME, the growth rate is

$$r^{me} = (1-p)\left[\frac{2^{\frac{1}{\alpha}}c^{-1}A_{H,t-1}^{\theta_S-1}}{\beta_S+1}(X_{g,s}^{\beta_S+1}-X_{u,s}^{\beta_S+1})+\frac{2^{\frac{1-\alpha}{\alpha}}A_{H,t-1}^{\theta_G-1}}{\beta_G+1}(1-X_{g,s}^{\beta_G+1})\right] -p(1-X_{u,s}) \quad \text{(B-9)}$$

Therefore, the positive composition effect and the negative brain drain effect are

$$C^{me}(p) = (1-p)\left[\frac{2^{\frac{1}{\alpha}}c^{-1}A_{H,t-1}^{\theta_S-1}}{\beta_S+1}(X_{g,s}^{\beta_S+1}-X_{u,s}^{\beta_S+1})+\frac{2^{\frac{1-\alpha}{\alpha}}A_{H,t-1}^{\theta_G-1}}{\beta_G+1}(1-X_{g,s}^{\beta_G+1})\right] \quad \text{(B-10)}$$

$$B^{me}(p) = p(1-X_{u,s}) \quad \text{(B-11)}$$

Derive them w.r.t. p and check them at $p=0$,

$$C^{me'}(0) = \frac{2^{\frac{1-\alpha}{\alpha}}A_{H,t-1}^{\theta_G-1}}{\beta_G+1}\left[1-(2c^{-1}A_{H,t-1}^{\theta_S-\theta_G})^{\frac{\beta_G+1}{\beta_G-\beta_S}}\right] - \frac{2^{\frac{1}{\alpha}}c^{-1}A_{H,t-1}^{\theta_S-1}}{\beta_S+1}\left[(2c^{-1}A_{H,t-1}^{\theta_S-\theta_G})^{\frac{\beta_S+1}{\beta_G-\beta_S}}-X_{u,s}^{**\beta_S+1}\right]+\frac{A_{F,t-1}-A_{H,t-1}}{A_{H,t-1}\beta_S}X_{u,s}^{**} \quad \text{(B-12)}$$

$$B^{me'}(0) = 1-X_{u,s}^{**} \quad \text{(B-13)}$$

The threshold of a beneficial migration in ME is

$$\widetilde{X^{me}} = \frac{A_{H,t-1}\delta\beta_S K}{(1+\beta_G)\left[E\beta_S+(1+\beta_S)(A_{F,t-1}-A_{H,t-1})\delta+(1+\beta_S)A_{H,t-1}\delta\beta_S\right]}$$

where $K = (1+\beta_G)(1+\beta_S)+2^{\frac{1}{\alpha}}c^{-1}A_{H,t-1}^{\theta_S-1}(1+\beta_G)(2c^{-1}A_{H,t-1}^{\theta_S-\theta_G})^{\frac{1+\beta_S}{\beta_G-\beta_S}}+2^{\frac{1-\alpha}{\alpha}}A_{H,t-1}^{\theta_G-1}(1+\beta_S)(1-(2c^{-1}A_{H,t-1}^{\theta_S-\theta_G})^{\frac{1+\beta_G}{\beta_G-\beta_S}})$.

Therefore, in ME, if the ex ante fraction of unskilled labor is greater than the threshold, i.e. $X_{u,s}^{**} > \widetilde{X^{me}}$, there exists a probability of migration p^* maximizing the growth rate. If the ex ante fraction is less than the threshold, migration is always detrimental to the domestic economy.

Similarly in SE, the growth rate is given by

$$r_{A,t}^{se} = \frac{2^{\frac{1}{\alpha}}c^{-1}A_{H,t-1}^{\theta_S-1}(1-p)(1-X_{u,s}^{**1+\beta_S})}{(1+\beta_S)} - p(1-X_{u,s}^{**}) \tag{B-14}$$

Therefore, the positive composition effect $C(p)$ and the negative brain drain effect $B(p)$ are

$$C(p) = \frac{2^{\frac{1}{\alpha}}c^{-1}A_{H,t-1}^{\theta_S-1}(1-p)(1-X_{u,s}^{**1+\beta_S})}{(1+\beta_S)} \tag{B-15}$$

$$B(p) = p(1-X_{u,s}^{**}) \tag{B-16}$$

$C^{se'}(0)$ and $B^{se'}(0)$ together give us the threshold in SE

$$\widetilde{X^{se}} = \frac{A_{H,t-1}\delta\beta_S(1+\beta_S+2^{\frac{1}{\alpha}}A_{H,t-1}^{\theta_S-1})}{E\beta_S+(1+\beta_S)(A_{F,t-1}-A_{H,t-1})\delta+(1+\beta_S)A_{H,t-1}\delta\beta_S} \tag{B-17}$$

APPENDIX C

THE EFFECT OF TERTIARY EDUCATION COMPOSITION ON ECONOMIC GROWTH

C.1 Developing Country List

Country Name	Frequency
Argentina	7
Armenia	11
Azerbaijan	4
Belarus	13
Bosnia and Herzegovina	5
Brazil	9
Brunei Darussalam	13
Cambodia	5
Chile	9
Colombia	8
Costa Rica	13
Croatia	12
El Salvador	9
Ethiopia	10
Georgia	13
Indonesia	5
Iran (Islamic Republic of)	6
Jordan	7

Country Name	**Frequency**
Kyrgyzstan	12
Lao People's Democratic Republic	9
Lebanon	12
Madagascar	7
Malawi	7
Malaysia	11
Mexico	12
Mongolia	13
Morocco	2
Mozambique	6
Namibia	5
Nepal	6
Panama	10
Philippines	8
Qatar	8
Republic of Korea	13
Republic of Moldova	13
Russian Federation	9
Saudi Arabia	14
Syrian Arab Republic	10
Thailand	10
The Former Yugoslav Republic of Macedonia	13
Turkey	13
Ukraine	12
Uruguay	12
Uzbekistan	6
Total	412

C.2 Developed Country List

Country Name	**Frequency**
Australia	12
Austria	11
Belgium	8
Bulgaria	12
Cyprus	11
Czech Republic	13
Denmark	11
Estonia	13
Finland	12
France	10
Germany	4
Greece	8
Hungary	14
Iceland	12
Ireland	13
Italy	12
Japan	14
Latvia	13
Lithuania	13
Malta	12
Netherlands	13
New Zealand	14
Norway	13
Poland	11
Portugal	11
Romania	13
Slovakia	13
Slovenia	12
Spain	13
Sweden	13
Switzerland	13

Country Name	**Frequency**
United Kingdom of Great Britain	14
United States of America	13
Total	394