City and Technology in Catching-up Economies: The Mechanisms of Selection, Sorting and Learning

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September 2014

Abstract. In fast catching-up economies, we see not only rapid increases in skilled labor and R&D investment but spatial concentration of skilled labor and hence production. The paper accounts for this empirical fact. As a catching-up economy grows closer to the technology frontier, knowledge spillovers from advanced countries decline and technology creation becomes increasingly more profitable than technology adoption, raising the demand for skilled workers who can better conduct technology “creation” activities relative to less skilled workers who conduct technology “adoption” activities. When this feature is combined with the facts that cities allow more active knowledge spillovers for spatial proximity and more able workers generate more profitable ideas, the observed correlations arise: high-ability workers invest more in human capital to become skilled workers (selection) who sort into cities with the most ability-worker residing the closest to the city center while paying the highest rents (sorting), and they can more efficiently boost their productivity of R&D activities using knowledge spillovers (learning). This pattern self-enforces with endogenous growth based on Romer’s (1990) mechanism. Among policy implications for fostering growth, urban rents control and subsidy to information technology can be justified in our framework.

Keywords: Urban agglomeration; skill upgrading; basic R&D activities; technology creation and adoption

JEL Classification: R12, O31, O18

The authors benefited from discussion with Hoyeon Kim and Minsung Kim. They are also grateful for seminar participants at Sungkyunkwan university.
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I. Introduction

Economic growth performance is diverse, ranging from the traditional advanced economies that took several centuries of industrialization, to recent catching-up economies and to many economies with little sign of convergence. Interestingly, fast catching-up economies exhibit not only rapid accumulation of human capital and active R&D investment but also high urban concentration and industrial clusters. Viewing fast catching-up economies as economies getting closer to the technology frontier, this paper attempts to account for how urban agglomeration, the composition of skilled and unskilled labor, and R&D investment evolve over the endogenous growth path.

Many catching-up countries are experiencing rapid urbanization without high urban unemployment even after the early development (industrialization) stages, which cannot be accounted for by the traditional Harris-Todaro (1970) rural-urban migration model. In particular, four East Asian cities, Tokyo, Osaka-Kobe, Hong Kong and Seoul, were in the list of the top 30 cities ranked by GDP, which produced 16% of global GDP in 2005. It is hard to deny that urbanization plays an important role in the process of economic growth of those countries by providing scale economies of agglomeration, such as labor market pooling, input sharing, and local knowledge learning, as noted by Marshall (1890).3

Although this clustering pattern may be weak for developed countries where urbanization has been finished a while ago and the implementation of regionally balanced growth is a policy concern, this observation seems real for many catching-up Asian

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1 In this paper, ‘city’ and ‘urbanization’ are used interchangeably with ‘cluster’ and cluster formation, respectively, since the local knowledge learning of agglomeration effects is the main theme of this paper.
2 Yusuf (2007) describes the rapid urbanization phenomena among East Asian countries and the importance of the urbanization process in their development: “Japan, China and the Republic of Korea accounted for 84% of East Asia’s GDP in 2005. Within these three countries, just six urban regions generate 45% of the aggregate domestic production. Moreover, 42% of Korea’s population reside in the Seoul–Incheon region and 40% of the population of Japan live and work in the metropolitan areas of Tokyo, Osaka, and Nagoya. Because of its size, China’s population and industrial production are more evenly distributed. Nevertheless, 80–85 million people, over 6% of the total population live in the metropolitan precincts of Shanghai, Beijing-Tianjin and the Pearl River Delta excluding Hong Kong and 37% of China’s GDP originates from the three sprawling regions. The notable characteristics of these urban regions, apart from size, is that they are attracting industries with high value added and are centers of knowledge intensive activities. The mega urban regions are not a passing phenomenon. They are likely to persist and to enlarge their economic footprints because they benefit from the advantages of market scale, agglomeration economies, location and the increasing concentration of talented workers.” (see page 1 of Yusuf, 2007).
3 See Duranton and Puga (2004) for a review of agglomeration economies. Alternative views find the presence of mega cities in developing economies on the political economy side, such as the so-called “first-city bias.”
economies. Aside from the large cities, we also see the workforce of skilled workers growing more disproportionately in cities than in non-cities. In the case of Korea, the Seoul metropolitan areas expand recently with a greater GDP share in the nation after the information technology development in the period of 1990s to the present. Even after reaching the overall urbanization rate of 80% in the 1980’s, major cities of Korea not only still expands gradually despite regulations against regional concentration but absorbs highly educated workers while unskilled workers tend to remain in the rural area, with a resulting skill gap between regions.

We argue that the following two mechanisms are crucial for fast growth of catching-up economies. (i) A country, with a narrow gap from the technology frontier, has greater incentives to invest in technology creation than in adoption, because its technology spillovers from advanced countries diminish with a lower productivity of technology adoption: “the catch-up mechanism.” (ii) Given their spatial structure, cities allow more active knowledge spillovers than non-cities since knowledge spillovers diminish over space in nature. When more able workers generate more profitable ideas, we can obtain the following self-selection mechanisms: (a) high-ability workers invest more in human capital to become skilled workers (selection), (b) they sort themselves into cities with the most ability-worker residing the closest to the city center despite paying the highest rents (sorting), and (c) they conduct technology creation activities in cities because there they can more efficiently boost their productivity of R&D activities using knowledge spillovers (learning): “the selection, sorting and learning mechanism.” These two mechanisms combined account for the observed correlations among skill investment, urbanization and economic performance among fast catching-up economies. Accordingly, from the policy perspectives, we should carefully consider the self-selection mechanisms behind the ideas-based growth and the time-dependent skill-location complementarity over the development path.

The catching-up mechanism stresses the importance of technology creation. Knowledge spillovers from advanced countries diminish with a country’s growth in nature, lowering the productivity of technology adoption. Unlike technology adoption, technology creation requires the new basic R&D, which cannot be replaced by the existing pool of basic ideas spilt over from advanced countries and therefore should be conducted by skilled workers. Both technology creation and adoption can be described by an endogenous growth model in line with a Romer’s (1990) variety expansion model. We assume that both
technology creation and adoption require development R&D process to commercialize original ideas. Basic R&D process creates new basic ideas, while development R&D process, using the pool of available basic ideas, produces differentiated intermediate goods that are used for technological improvements.

The selection, sorting and learning mechanism includes how a city attracts skilled workers who raise their productivity of basic R&D activities through inner-city knowledge spillovers and thus economic growth. This raised productivity in turn attracts skilled workers into the city, reinforcing urban agglomeration and economic growth as well. This process leads to the complementarity between urbanization and basic R&D activities of skilled workers. We also provide a micro self-selection mechanism describing how knowledge spillovers among skilled workers in a city are created and affect their productivity. More able workers can generate more knowledge spillovers to others, and as the distance between senders and receivers of knowledge spillovers increases, knowledge spillovers get attenuated before reaching receivers. As a result, a location that is closer to the center of a city forms a higher level of knowledge spillovers, attracting more able workers despite paying a higher rent.

The catching-up mechanism draws on the following literature. Aghion and Howitt (1996) investigate the role of the composition between research and development in a Schumpeterian growth model. Vandenbussche et al. (2004) examine the role of the composition of various human capital in a model of technology adoption and innovation. Ha et al. (2009) show that a narrower distance of a country from the technology frontier causes economic growth to be the more positively correlated with highly skilled labor and basic R&D activities with some empirical evidence. While similar to the Aghion and Howitt’s (1996) theoretical implications, our paper examines not only the interaction between human capital and R&D investment, but also the composition between technology adoption and technology creation.

The idea of spatial sorting has been addressed in the growing literature of the urban wage premium which addresses sorting as an essential element (e.g., Combes et al., 2008; Mion and Naticchioni, 2009; Matano and Naticchioni, 2011; Bacolod, Blum and Strange, 2009; Kim, 2014). We share a similar spirit with the literature but we look at spatial sorting in the context of a more macro growth with knowledge spillovers.4

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4 In contrast to ability sorting, Glaeser and Maré (2001) propose a learning hypothesis, with empirical evidence that workers in cities earn 33% more than those outside cities, and also suggest that cities can help accumulate human capital more rapidly. Meanwhile, Bacolod et al. (2008) show that larger cities are more
The literature on knowledge spillovers is based on the hypothesis that the interactions among various workers lead to sharing of knowledge spillovers which raises their productivity and wages. Marshall (1890), Lucas (1988), Glaeser (1999), among others, investigate this mechanism. Rauch (1993), Acemoglu and Angrist (2000) and Moretti (2004a and 2004b) among others provide evidence of positive effects of knowledge spillovers on wages.

In addition, there is more direct empirical evidence for the idea that cities facilitate innovation, diffusion, and sharing of knowledge and skill. Jaffe et al. (1993) estimate knowledge flows by tracing patent citations. They provide empirical evidence that inventors tend to cite patents invented by those from the same city much more likely than randomly drawn cited patents. Audretsch and Feldman (1996) demonstrate that innovative activities measured by significantly new product introductions tend to cluster in the industries where new economic knowledge is important for business performance. Chung et

skilled, and that the urban wage premium is larger for workers with higher cognitive and social skills, but not with stronger motor skills and physical strength. Similarly, Matano and Naticchioni (2012), exploring the sources of the urban wage premium using Italian data for 1986-2003, show that the ‘coordination effect’, that is derived from the better match between workers and firms, is relevant for skilled workers, while the ‘learning effect’, that human capital accumulation is faster in more dense areas, for unskilled ones.

Lucas (1988) argues that “human capital accumulation is a social activity, involving groups of people in a way that has no counterpart in the accumulation of physical capital”. In addition, Newton’s well-known statement that “If I have seen farther than others, it is because I was standing on the shoulders of giants” implies strong effects of knowledge spillovers.

Compared to others, Acemoglu and Angrist (2000) provide evidence of small social returns that are estimated to be approximately one percent above private returns, by taking advantage of natural experiments of compulsory schooling laws and child labor laws in the U.S.
al. (2009) provide empirical evidence supporting our mechanisms that the rising skill-premium arising from skill-biased technological change is found in cities only in the U.S. This paper adds to the literature by analyzing the dynamic incentives that catching-up economies shape their economic structure in order to benefit from urban knowledge spillovers for technology creation.

Aside from accounting for the main correlations, our model also has the following results. First, getting closer to the technology frontier boosts city size and the rental price relative to wage, by increasing the demand for urban skilled workers conducting basic R&D activities for technology creation. This in turn lowers the demand for less skilled workers and technology adoption activities. Second, the equilibrium rent of a location falls with the distance from the urban center. This spatial pattern of rents depends on urban knowledge spillovers, without invoking the commuting cost argument. Third, with urban rents control (e.g., taxing the landowners’ rental income and subsidizing urban rents), the economy grows faster as a result of increasing the supply of skilled workers, city size, and the productivity of basic R&D activities. Last, advancements in information technology lowers the geographic attenuation rate of information transfers and raises the incentive to become skilled workers, boosting city size and economic growth.

The rest of the paper is organized as follows. Section II presents the model, and derives the demand and supply of various types of human capital and R&D investment. Section III characterizes the equilibrium structures of R&D and human capital investment and the equilibrium rent scheme, and Section IV presents comparative statics analyses based on Section III. Section V concludes. In addition, Appendix A analyzes the knowledge spillovers of the urban agglomeration effects and shows the determination of the equilibrium rent scheme. Finally, Appendix B presents other comparative statics analyses.

II. The Model

1. The Environment and Sketch of the Model

This section describes the model and the equilibrium structure of human capital and R&D investment by analyzing knowledge spillovers (see Appendix A) and urban agglomeration effects.

We consider a two-period overlapping generations model. In each period, a
measure one of a continuum of workers living two periods is born with heterogeneous abilities \( a_j \) that is uniformly distributed on \([0, 1]\) with a specific form:

(1) \[ a_j = j \in [0,1]. \]

They invest in education in period one, and work and consume in period two. The education cost is paid with a fixed fraction of their income in period two. The supply of three types of workers is endogenously determined. In his first period, by obtaining relevant education, the worker chooses one of the three types of human capital investment leading to a different skill level: less skilled workers \( U \), skilled workers \( S \), and highly skilled workers \( H \). We normalize the workforce at unity.

(2) \[ U + S + H = 1. \]

The more able he is, the less he pays for acquiring the same level of education. In the second period, the worker is employed in one of the three research sectors: (i) basic R&D of the creation sector (highly creative sector), (ii) development R&D of the creation sector (creative sector), or (iii) development R&D of the adoption sector (less creative sector). The only state variable is the publicly available pool of ideas, which simplifies the model’s dynamics because individuals do not optimize on the pool of ideas. The model produces an endogenous growth, because this pool as the aggregate of individuals’ ideas grows over time.

Now, we discuss the spatial structure of the model, city vs. non-city. It is a line with a center that is described by location \( x=0 \) (see Figure A1). Given the dense spatial nature, only cities provide externalities of knowledge spillovers. More able workers produce greater ideas externalities, which, as will be shown later, are more efficiently taken by highly skilled workers \( H \), and therefore city size can be said \( H \) in equilibrium. Information transfers dissipate over distance, limiting knowledge spillovers at the rate of \( \delta \): with the wider distance \( \tau \) between the sender and the receiver of information, the receiver can obtain the less information, because information attenuates geographically by a factor of \( \exp(-\delta \cdot \tau) \) with a positive geographic attenuation rate \( \delta \). Landowners supply fixed housing services and take rents \( R \) from workers. To simplify the story, we normalize non-city rents at zero.

The technology sector consists of (i) technology adoption and (ii) technology
creation sub-sectors. In the adoption sector, development R&D activities of \( U \) produce different intermediate goods \( x_D(i) \) using freely available basic ideas for technological improvements. The specific knowledge \( A_D \) of less skilled workers, that is public knowledge to the industry, increases their productivity, and accumulates through learning-by-doing (henceforth, LBD). The new basic ideas that flow into the adoption sector increases with the country’s distance from the technology frontier, which is taken external for analytical convenience.

On the other hand, in the creation sector, development R&D activities of \( S \) produce various intermediate goods \( x_C(i) \) using the pool of basic ideas for technological improvement. The specific knowledge \( A_C \) of skilled workers, that is public knowledge in the industry, raises their productivity, and accumulates through LBD. These intermediate goods are adapted from corresponding basic ideas, and are traded at monopolistic competitive markets. And highly-skilled workers \( H \) create new basic ideas by engaging in basic R&D activities, flowing into the creation sector in each period. If they reside closer to the city’s center, they can adopt a higher level of knowledge spillovers, leading to a higher productivity of basic R&D activities. The inventor of each new basic idea is assumed to monopolize his profit for one period. The firm produces the final output by combining three inputs: raw labor, physical capital, and technology. Raw labor and physical capital are supplied by world markets at exogenously given world market prices.

As will be shown later, our spatial equilibrium establishes based on multiple self-selection mechanisms. First, workers whose ability is greater than a certain threshold level \( a^*_H \) become highly-skilled workers by obtaining appropriate education, and migrate to the city. Second, only highly-skilled workers \( H \) conduct basic R&D (highly creative) activities. Third, among highly-skilled workers, most-able workers reside at the city center, paying higher rents and the rest sort themselves away from the center in a descending order of ability. Rents fall with the distance from the center. The underlying micro mechanism is that the productivity of basic R&D depends on ability and city size: \( B(a; H) \) with \( B_1 > 0 \) and \( B_2 > 0 \).

In the spatial sorting equilibrium where highly skilled workers live in a city in descending order of their ability from its center to the periphery. As will be shown later, this equilibrium arises when the benefits from information spillovers balance with the rental cost. A worker with ability \( a \) residing at the equilibrium location \( x \in [-H/2, H/2] \) (see Figure A1), whose equilibrium distance from the city’s center \( z \) is \( z = |x| = (1-a)/2 \), is
assumed to create knowledge spillovers $I(z)$ per unit of time:

$$I(z) = I(0) \exp(-\theta z)$$

$$= I(0) \exp \left(-\frac{\theta(1-a)}{2}\right), \text{ with } z = \frac{1-a}{2} \text{ in equilibrium,}$$

where $I(0)$ represents the amount of knowledge spillovers created by the worker with ability $a = 1$ residing at $z = 0$, and $\theta$ is a scale parameter for “ideas creation.”

A worker adopts knowledge spillovers created by all city workers with his absorptive capacity $c(a)$.

The within-city sorting and rents are based on the fact that high-ability workers can adopt a higher level of knowledge spillovers, increasing their productivity of basic R&D activities and thus wages. The following two micro features lie behind this. First, a location closer to the center can provide the higher level of information flows (spillovers) per unit of time. Second, higher ability helps adopt higher level of information per unit of time. In contrast, lower ability workers among $H$ are forced to move farther away from the city’s center. This is because lower ability can help adopt only a lower level of knowledge spillovers, even in the location closer to the center, and also because locations closer to the center entail higher rents. Both rents and information channeling capacity of the public hub at each location supports the spatial equilibrium of matching ability with location. Workers do not move farther away from their equilibrium locations to the locations with lower rents since doing so leads to a low net gain: the information handling capacity of the public hub there is too low for a high-ability individual – the wage gain is thus limited, despite rents saving.

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8 Here, the population density is assumed to be fixed at unity. If the density is $f$, then the information attenuation rate $\delta$ in the model has to be replaced with $\delta / f$. Our model does not consider the negative effects of urban agglomeration such as congestion and pollution. To incorporate these effects into the model as simply as possible, we would used $\delta$ such that $\delta$ is large in cities with high congestion because transfers of tacit information require a face-to-face contact which becomes difficult in congested cities.

9 Facilities for social gathering and communication such as wireless LAN, telecommunication, transportation, restaurants, pubs, cafes, etc. are poorly provided in cheaper locations.

10 Additional preference-side factors may involve the costs that limit a high-ability worker to move from his equilibrium location to a remote location: (i) psychological costs of lowering social status associated with locations, (ii) opportunity cost of joining clubs of lower ability workers, or (iii) opportunity cost of worsening safety or other negative urban amenities.
2. Production, Human Capital, and Technology

2.1. Production

The final output of the economy is produced by the Cobb-Douglas technology of

\[ Y_t = T_t^\gamma K_t^\nu L_t^{1-\gamma-\nu}, \]

where \( T_t \) represents the level of technology and is a function of various human capital composition to be specified later; \( K_t \) is physical capital; and \( L_t \) is raw labor. We assume that the final output market is competitive and consists of a unit measure of identical firms. The markets for capital and raw labor are internationally open, and hence the interest rate and the wage rate for raw labor are exogenously given in the framework of a small open economy.\(^{11}\) We also assume that the transportation cost to any location is zero.

2.2. Human capital and technology structure

A measure unity of workers as in (2) are classified in accordance with their skill levels that depend on education investment: less skilled workers \( U \) employed in the technology adoption sector, and skilled workers \( S \) and highly skilled workers \( H \) both of whom are employed in the technology creation sector. All labor supply a unit of time to the market inelastically.\(^{12}\)

The technology sector consists of technology adoption \( D_t(U) \), and technology creation \( C_t(S) \), and the technology level \( T_t \) is a function of \( D \) and \( C \) with a constant elasticity of substitution (\( \sigma \)) between them:

\[ T_t = \left[ D_t(U)^{\frac{\sigma-1}{\sigma}} + \kappa C_t(S)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\sigma-1}}, \]

where \( \kappa>1 \) implying the relative importance of creation. For analytical simplicity, we assume that the gross substitutability between technology adoption and creation processes is infinite, \( \sigma = \infty \):

\(^{11}\) These assumptions help us focus on the effects of human capital allocation on technology. And this does not sound unrealistic considering that the current world economy is highly globalized. Note also that the steady state growth rate of GDP is equal to that of technology, affected neither by physical capital accumulation nor by raw labor supply.

\(^{12}\) We can assume that the efficiency unit of workers increases, which does not affect the results of the paper.
Following the Romer’s (1990) variety expansion model, we describe technologies $D$ and $C$ that are determined by combining “blueprints” $x_D(i)$ and $x_C(i)$” (intermediate goods) respectively:

$$ D_t(U) = \left[ \int_0^{G_D} x_D(i)^{\alpha-1} \, di \right]^{\frac{\alpha}{\alpha-1}} $$

and

$$ C_t(S) = \left[ \int_0^{G_C} x_C(i)^{\alpha-1} \, di \right]^{\frac{\alpha}{\alpha-1}}, $$

where $G_D$ represents the pool of all basic ideas appropriate for technology adoption at time $t$, $G_C$ is the comparable counterpart for technology creation, and $\alpha > 1$ indicates the usual high elasticity of substitution among various intermediate goods.

The pool of all basic ideas available in each sector is described as follows. The flow of new basic ideas in the adoption sector is due only to knowledge spillovers from advanced countries that increase with technological distance. However, the flow of new basic ideas in the creation sector is due not only to knowledge spillovers from advanced countries, but also to basic research activities of $H$.

An innovator, a highly skilled worker with ability $a_j$, creates new basic ideas as many as $B(a_j;H)G_{t-1}$ at time $t$, where $G_{t-1}$ is the total amount of “basic ideas” accumulated in the aggregate economy at time $t-1$ that is freely accessible and non-appropriable.

Here we assume that abilities of workers are uniformly distributed with $a_j = j \in [0,1]$. We also assume that the higher the worker’s ability, the more knowledge spillovers the worker can enjoy from the same sources, and the less cost he pays for getting education to become a highly skilled or a skilled worker.

Then the pool of basic ideas invented by the technology creation sector $G_C$ at time $t$ is described by:
where  \( \overline{B}(H) = \frac{1}{H} \int_{a_j}^{a_H} B(a_j; H) \, dj = \frac{1}{H} \int_{a_j}^{a_H} B(a_j; H) \, dj \), and  \( H \) represents the equilibrium number of highly skilled workers  \( (H = 1 - a_H^*) \) as well as city size. Here, workers whose ability is greater than  \( a_H^* \)  become highly skilled workers and migrate to the city, which is formally proved in Subsection 2.4.

Further,  \( B(a_j; H) \), representing the equilibrium productivity of basic R&D activities of highly skilled workers with ability  \( a_j \) residing in the city with size  \( H \), increases in city size  \( H \) and in the workers’ ability  \( a_j \). This is because  \( B(a_j; H) \) is affected by knowledge spillovers from agglomeration effects of the city with size  \( H \), and because higher ability workers adopt more of knowledge spillovers. Appendix A presents a simple micro-mechanism that shows how city size and ability affect  \( B(a_j; H) \).

The pool of all basic ideas available in the adoption sector  \( G_D \) accumulates over time by:

\[
G_{Dt} = \left[ 1 + d(T - T_{t-1}) \right] G_{Tt-1}, \quad \text{and}
\]

where the term  \( d(T - T_{t-1}) \) indicates that a greater technology gap  \( T - T_{t-1} \) from the world frontier  \( T \) allows a greater productivity of the adoption sector, as the technology level approaches the technology frontier  \( T \);  \( d(T - T_{t-1}) \) monotonically decreases to zero; and  \( G_{Tt} \) is the overall technology level, which grows in accordance with

\[ 13 \text{ The productivity of basic R&D activities of highly skilled workers depends not only on city size } H, \text{ but also on the location of these workers in the city. In equilibrium, the workers’ abilities are allocated to specific locations in the city by matching workers’ abilities from the highest to the lowest in descending order with locations starting from the city’s center to its periphery, which is proven in Appendix A. Thus, the productivity of basic R&D activities in equilibrium depends only on workers’ ability and city size.} \]
One unit of the intermediate goods $x_{jt}$ is produced using one unit of human capital $l_{jt}$ by the simple, linear production technology of

\begin{equation}
    x_{jt} = l_{jt} \text{ for } j = D, C,
\end{equation}

where $x_{jt}$ with $j = D, C$ represents the intermediate goods produced by the technology adoption ($j = D$) and technology creation ($j = C$) processes respectively.

Next, the human capital levels of technology adoption and creation sectors are defined as $\int_{0}^{G_{D}} l_{D}(i)di$ and $\int_{0}^{G_{C}} l_{C}(i)di$, respectively. They are expressed as linear functions of “effective” unskilled and skilled workers, respectively:

\begin{equation}
    \int_{0}^{G_{D}} l_{D}(i)di = A_{D_{t-1}}U,
\end{equation}

\begin{equation}
    \int_{0}^{G_{C}} l_{C}(i)di = A_{C_{t-1}}S,
\end{equation}

where $A_{C_{t}}$ and $A_{D_{t}}$ represent the non-appropriable specific knowledge accumulated through LBD in the technology creation and technology adoption sectors.

The dynamic of LBD in each sector is described by

\begin{equation}
    A_{C_{t}} = (1 + \phi_{C}S)A_{C_{t-1}}, \text{ and}
\end{equation}

\begin{equation}
    A_{D_{t}} = (1 + \phi_{D}U)A_{D_{t-1}},
\end{equation}

where $\phi_{i}$ with $i = C, D$ represents the productivity of LBD. However, to simplify the
model, we do not consider the growth effect of LBD in what follows.

The adoption sector demands labor $U$ to produce intermediate goods, whereas the creation sector demands $S$. The production of intermediate goods involves the development research process. Thus, the sizes of $U$ and $S$ imply the levels of development research investment in the adoption and creation sectors, respectively.

We assume that the intermediate goods market of the adoption sector is competitive, whereas that of the creation sector is monopolistically competitive. That is, in the adoption sector, its pool of basic ideas are freely available, and its adapted intermediate goods are less refined and less logically consistent, whereas, in the creation sector, the adapted intermediate goods are more refined, more logically consistent, and protected by patents. Based on the discussions above, we now can reexpress technology and output as follows:

\[
T = G_{t-1}^{\frac{1}{\gamma}} \left( (1 + d)^{\frac{1}{\gamma}} A_{D_{t-1}} U + \kappa(\overline{B}(H) H)^{\frac{1}{\gamma}} A_{C_{t-1}} S \right),
\]

\[
Y = \left( G_{t-1}^{\frac{1}{\gamma}} \left( (1 + d)^{\frac{1}{\gamma}} A_{D_{t-1}} U + \kappa(\overline{B}(H) H)^{\frac{1}{\gamma}} A_{C_{t-1}} S \right) \right)^{\gamma} K^\nu L^{1-\gamma-\nu},
\]

where $d = d(\overline{T} - T_{t-1})$.

(17) and (18) imply the following. First, because of market failure assumptions such as monopolistic competition at the technology creation sector, knowledge spillovers, the social capital nature of basic ideas, and the LBD mechanism, the equilibrium allocation differ from the Pareto optimal allocation as in Romer (1990). In addition, because the prices of $K$ and $L$ are given exogenously and fixed, $K$ and $L$ increase with $T$, such that their marginal productivities equal these fixed prices. Therefore, it is straightforward to prove that the economy grows at the same rate that $T$ does. Finally, the main driving engine of economic growth is the accumulation of all basic ideas, $G_{t} = [1 + d(\overline{T} - T_{t-1}) + \overline{B}(H) H] G_{t-1}$ (i.e., social capital of the economy) that increases final output in the future.15.

14 For the optimal allocation, H and S need to be increased to higher levels.

15 From the setup of the model, we can easily infer that if $G_{t}$ increases, economic growth increases in the
3. Labor Demand

The demand for less skilled workers is described by:

\[ w(U) = \frac{\partial Y}{\partial U} = \gamma Y \left(1 + d\right)^{-\frac{1}{\alpha}} \frac{A_{D_{t-1}}}{A_{D_{t-1}} - A_{C_{t-1}} - \kappa(B(H)H)^{-\frac{1}{\alpha}}} \cdot \]

Because the market for intermediate goods of the creation sector is monopolistically competitive, \( p_c^i(i) = \frac{\alpha}{\alpha - 1} \frac{1}{A_{C_{t-1}}} w(S) \) should hold. Using this and another equilibrium condition \( p_c^i(i) = \frac{\partial Y}{\partial x_c(i)} = \frac{1}{A_{C_{t-1}}} \frac{\partial Y}{\partial S} \), we can derive:

\[ w(S) = A_{C_{t-1}} \frac{a-1}{a} p_c^i(i) = \frac{a-1}{a} \frac{\partial Y}{\partial S} \]

\[ = \frac{\alpha-1}{a} \frac{\gamma Y}{\left(1 + d\right)^{-\frac{1}{\alpha}}} \frac{\kappa(B(H)H)^{-\frac{1}{\alpha}} A_{C_{t-1}}}{A_{C_{t-1}} - A_{D_{t-1}} - \kappa(B(H)H)^{-\frac{1}{\alpha}}} \cdot \]

Note that the earnings of skilled workers increases in \( H \), \( B(H) \), and \( A_{C_{t-1}} / A_{D_{t-1}} \), and decreases in \( d \) and \( S \), which is quite intuitive.\(^{16}\)

Highly skilled workers contribute to the creation of new ideas, which are used to produce intermediate goods in the creation sector, and their profit per idea is \( \pi \) for one period.\(^{17}\) Considering that \( \pi = \frac{1}{\pi^{-1}} \frac{w(S)}{A_{C_{t-1}} S} \frac{A_{C_{t-1}} S}{A_{C_{t-1}} G_{C_{t}}} \cdot \)

\(^{16}\)To be more precise, we should use the results of the comparative statics analyses in Section IV.

\(^{17}\)To simplify the model, the paper assumes that the property right of a new idea will be transferred to the firm in the next period.
This equation implies that the highly skilled worker’s wage is positively associated with $B(a_j; H)/B(H)$, $S$, and $w(S)$, i.e., complementarity between $H$ and $S$.

4. Household’s Choice of Education

The economy is populated by a unit measure of workers with different abilities living for two periods. A worker $j$ is born with a certain level of ability ($a_j = j \in [0,1]$) that is uniformly distributed on $[0, 1]$. And the worker is endowed with one unit of time that is supplied inelastically in his second period.

The worker decides how much to invest in education in the first period by considering his ability, education costs, and wage rates for three different types of human capital. This would in turn determine which type of human capital he owns in his second period. In this way, the demand and supply for each type of human capital jointly determine equilibrium wage rates, research investment, and thus technology and output growth rates.

We assume that the education cost measured in the second period output to become a skilled worker is $C_s/m(a)$, whereas that to become a highly skilled one is $C_h/n(a)^{\text{18}}$, where $m(a)$ and $n(a)$ increase in the worker’s ability $a$, and $C_s$ (resp., $C_h$) represent the inefficiency of the education system for skilled workers (resp., highly skilled workers). We also assume that with no education, workers become less skilled workers.

With these simplifying assumptions, we can easily derive the critical level of ability $a_s^*$ such that

\begin{equation}
(22) \quad w(S) - \frac{C_s}{m(a)} w(S) > w(U) \Rightarrow
\end{equation}

\text{18} The resources required for education is assumed to be proportional to knowledge, which increases the student’s future wage proportionally. Thus, the tuition for education is proportional to the student’s future wage.
where \( m^{-1}(\cdot) \) is the inverse function of \( m(a) \), increasing in \( a \). The worker with the ability greater than or equal to \( a_S^* \) will get educated to become a skilled worker by paying the education cost \( \frac{C_S}{m(a)}w(S) \). Based on the simplifying assumption that knowledge spillovers are not essential for their productivity compared to highly skilled workers, both skilled and less skilled workers reside outside the city with paying zero rent.\(^{20}\)

Similarly, the worker with ability \( a_j \) that is greater than or equal to \( a_H^* \) will get education to become a highly skilled worker. Note here that \( n^{-1}(\cdot) \) is the inverse function of \( n(a_j) \), increasing in \( a_j \).

\[
(23) \quad w(a_j) - \frac{C_H}{n(a_j)}w(a_j) - R(a_j) > w(S) \quad ^{21}
\]

where \( R(a_j) \) is the equilibrium rent that the worker with ability \( a_j \) pays for his location.

We assume that \( a_H^* > a_S^* \) should hold and highly-skilled workers retain human capital that includes that of skilled workers.

5. Determination of the Equilibrium Rent\(^{22}\)

\(^{19}\) If \( (\alpha - 1)\kappa a_{C_{-1}}(\overline{B}(H)H)^{\frac{1}{c_1}} - \alpha \alpha A_{D_{-1}}(1 + d)^{\frac{1}{c_1}} < 0 \), then a corner solution happens with \( a_S^* = 1 \).

\(^{20}\) If skilled workers can obtain knowledge spillovers by residing more closely to the city, then they must pay higher rents than less skilled workers, because of the limited supply of land in a specific location. This can reduce the supply of skilled workers depending on the relative magnitude of two conflicting forces: higher rents and increased spillover effects.

\(^{21}\) If \( B(0)^{S} - (\alpha - 1)(\overline{B}(H)H) < 0 \), then a corner solution occurs with \( a_H^* = 1 \).

\(^{22}\) For a more detailed analysis of this subsection, refer to Appendix A. While much research focuses on the household’s choice of location considering the trade-offs between the commuting cost to CBD and rents (e.g., Abdel-Rahman and Anas (2004), Behrens et al. (2010), and others), our paper on the firm’s choice of location considering the trade-offs between a specific location’s production amenities and rents in the presence of heterogeneous firms. Thus, our model describes an assortive matching between location and firm within a city.
This subsection describes how the equilibrium rent scheme is determined. For this, firstly, posit that in equilibrium, highly skilled workers in the city are located in descending order from its center according to the magnitude of their ability, with higher ability workers located more closely to the city’s center. Here we describe the city with size $H$ by a real line $[-H/2, H/2]$, as in Figure A1.

We assume that landowners take a fixed fraction $\psi$ with $0 < \psi < 1$ of the entire benefit of knowledge spillovers of highly skilled workers to reside in the city through rental income. The magnitude of this fraction depends on the landowner’s bargaining power based on the Nash bargaining. We assume this fraction is fixed in our model. Given these, the equilibrium rent $R(a^*_H)$ for workers with ability $a^*_H$ is determined by dividing the wage gain net of education cost through the Nash bargaining:

$$R(a^*_H) = \psi \left( 1 - \frac{C_H}{n(a^*_H)} \right) \left( w(a^*_H) - w(0) \right)$$

(24)

$$= \psi \left( 1 - \frac{C_H}{n(a^*_H)} \right) \left( B(a^*_H; H) - B(0) \right) \cdot G_{cl^{-}} \pi$$

$$= \psi \left( 1 - \frac{C_H}{n(a^*_H)} \right) \frac{B(a^*_H; H) - B(0)}{\alpha - 1} \frac{S}{BH} w(S)$$

where $w(0)$ represents the “hypothetical” wage rate if highly skilled workers reside outside the city without benefiting from any knowledge spillovers, and $B(0)$ is the comparable productivity of basic R&D activities without urban knowledge spillovers.

We can rearrange (21) as a fraction of earnings after the education cost:

$$\frac{R(a^*_H)}{1 - \frac{C_H}{n(a^*_H)} w(a^*_H)} = \frac{\psi (w(a^*_H) - w(0))}{w(a^*_H)} = \psi \left( 1 - \frac{B(0)}{B(a^*_H; H)} \right)$$

(25)

where the term $\left( 1 - \frac{C_H}{n(a^*_H)} \right) w(a^*_H)$ represents the net earnings after subtracting the education cost. Here (25) implies that the marginal worker’s (the lowest ability worker’s) rental price ratio to wage depends only on the productivity of basic R&D activities inside the city in equilibrium.
relative to that outside the city.

With a given equilibrium scheme of rents \( \{R(j), j \in [0,1]\} \), a highly skilled worker in the city should not move from his equilibrium location to other locations. We call the conditions enforcing this spatial separation as “incentive compatibility conditions.” These conditions imply: If a worker migrates from his equilibrium location to a location that is closer to the center, the rent increase must be greater than the wage increase caused by the higher knowledge spillovers, i.e., the increased productivity of basic R&D activities. Conversely, if a worker migrates to a location that is more remote from the center, the rent decrease cannot dominate the wage decrease: this is because of the following. The maximum capacity of managing information flows at the public hub of each location is set to the level that its residents in equilibrium can adopt. A remote location taken by a low-ability worker has a low information processing capacity, so even a high-ability worker cannot extract information comparable to his ability but limited by the location’s equilibrium capacity. This assumption deters workers with any ability from migrating into the neighborhood where lower ability workers reside and is more remotely located from the city’s center in equilibrium.

In equilibrium, lower ability workers voluntarily migrate farther away from the city’s center, considering both their lower capacity to adopt knowledge spillovers and lower rents for locations far from the center. In contrast, higher ability workers can afford to pay more for locations closer to the city’s center, because they can adopt more knowledge spillovers, increasing their productivity of basic R&D activities and wage, than lower ability ones. Thus, there exists a complementary relationship between location and ability. Note that rental structure combined with the information processing capacity of each location provides a self-selection mechanism for aligning ability with location in a descending order of ability from the city’s center.

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23 See Appendix A for a more detailed analysis.
24 Intuitively, if the rent increase is less than the productivity increase, then the demand for locations closer to the center increases, thus raising the bargaining power of landlords. This in turn increases rents of these locations until the incentive comparability equation of (A8) is satisfied.
25 For a further analysis on this, refer to Appendix A.
26 Even when there exist a number of cities with their different sizes given exogenously, the optimal and equilibrium pattern of matching between locations and workers’ abilities still applies as in this paper. The matching between workers and locations in all cities with their equilibrium amounts of knowledge spillovers proceeds in descending order both of workers’ ability starting from its highest level and of the location’s amount of knowledge spillovers from its highest amount among all cities in equilibrium. In other words, the higher abilities are matched with the locations with the higher amount of knowledge spillovers among all
Using the productivity of basic R&D activities of the worker with ability \( a \) at location \( x \) as \( V(a, x; H) \), we can finally derive the equilibrium rent scheme satisfying the incentive compatibility conditions, derived in Appendix A, is:

\[
(A8) \quad \frac{S}{\alpha - 1} \frac{V(a, x; H) - V(a, x^*; H)}{B(H)H} w(S) = \frac{S}{\alpha - 1} \frac{V(1-2x^*, x; H) - V(1-2x^*, x^*; H)}{B(H)H} w(S) < R(1-2x^*) - R(1-2x^*)
\]

\[= \psi \frac{S}{\alpha - 1} \frac{V(1-2x, x; H) - V(1-2x^*, x^*; H)}{B(H)H} w(S) \text{ for all } x < x^* \in \left[0, \frac{H}{2}\right]
\]

The first term implies the marginal benefit from idea creation when moving closer to the center and the third term is the opportunity cost of greater rents. In equilibrium, a worker residing at location \( x^* \in [0, H/2] \) has the ability \( a = 1-2x^* \), because in equilibrium, highly skilled workers in the city are located in a descending order according to the magnitude of their ability.

Appendix A shows that productivity and wage as well as the equilibrium rent for all workers in the city increase in city size \( H \), and decrease in the geographic attenuation rate \( \delta \) and the information creation factor \( \theta \).

### III. Equilibrium Allocations of Human Capital and R&D Investment

It is clear that \( \overline{B}(H) = \frac{1}{H} \int_{0}^{H} B(a_j; H) \, dj = \frac{1}{H} \int_{-H}^{0} B(a_j; H) \, dj \) decreases in \( H \), because \( B(a_j; H) \) increases in ability \( a_j \). We can also easily infer that \( \overline{B}(H)H \) increases in \( H \), because \( B(a_j; H) > 0 \).

From (23) and (24), we have:

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Cities. Note here also that cities can have different attenuation rates depending on their efficiency of transportation and communication infrastructures, resulting in different city sizes, wage rates, rental costs, productivities, and growth rates.
Equations (26), (27), and (28) determine the relationships among \( H \), \( S \), and \( U \). Further, (26) implies a positive relationship between \( H \) and \( S \). Based on the assumption that the direct effect of an increase in \( H \) on \( S \) that is negative due to \( \partial(l - H)/\partial H = -1 \) is greater than the indirect general equilibrium effect on \( S \) that is positive due to \( \partial(-a_S^*)/\partial H \),\(^27\) (27) implies a negative relationship between \( H \) and \( S \). Using these relationships, (26) and (27) yield comparative statics results with respect to changes in various exogenous parameters in Section IV.

Note here that because (26), (27), and (28) imply that \( H \), \( S \), and \( U \), are

\[
H = 1 - a_H^* = 1 - n^{-1} \left( C_H \frac{SB(0)}{\psi(SB(0) - (\alpha - 1)\overline{B}(H)H)} \right).
\]

\[
S = a_H^* - a_S^* = 1 - H - m^{-1} \left( C_S \frac{(\alpha - 1)\kappa A_{\alpha-1}(\overline{B}(H)H)^{1/\gamma}}{(\alpha - 1)\kappa A_{\alpha-1}(\overline{B}(H)H)^{1/\gamma} - \alpha A_{\alpha-1}(1 + d)^{1/\gamma}} \right).
\]

\[
U = a_S^* = m^{-1} \left( C_S \frac{(\alpha - 1)\kappa A_{\alpha-1}(\overline{B}(H)H)^{1/\gamma}}{(\alpha - 1)\kappa A_{\alpha-1}(\overline{B}(H)H)^{1/\gamma} - \alpha A_{\alpha-1}(1 + d)^{1/\gamma}} \right).
\]

27 The indirect effect of \( \frac{\partial}{\partial H}(-a_S^*) \) in (24), that an increase in \( H \) indirectly affects \( S \) by increasing the pool of available basic ideas to be developed for technology creation, is positive due to the complementary relationship between \( H \) and \( S \). For this indirect effect to be less than the direct effect, we specifically assume that the elasticity of \( m(a_S) \), \( \eta_m = \frac{\partial m(a_S)}{\partial a_S} \frac{a_S}{m(a_S)} \), is large enough and/or that \( \frac{1}{(H)(H)} \frac{\partial B(H)(H)}{\partial H} \) is small enough such that \( \frac{\partial S}{\partial H} = -1 + \frac{\alpha A_{\alpha-1}(1 + d)^{1/\gamma}}{\eta_m (\alpha - 1)\kappa A_{\alpha-1}(\overline{B}(H)H)^{1/\gamma} - \alpha A_{\alpha-1}(1 + d)^{1/\gamma}} \frac{1}{(H)(H)} \frac{\partial B(H)(H)}{\partial H} < 0 \). This assumption implies that the education system for \( U \) to become \( S \) may be very inefficient. This is consistent with the observation that many countries, particularly most East Asian countries, have been struggling to shift the emphasis of their education system to enhancing creativity.
determined independently of \( G_{t-1} \), (18) implies that as \( G_t \) increases, \( Y_{t+1} \) increases.

### IV. Comparative Statics

This section presents some comparative statics analyses based on the results provided in the previous section. The main causal inferences in these analyses hinges on the following recursive idea. An exogenous change in a parameter affects \( H \) through equations (26) and (27). Then city size responds positively to \( H \), which in turn affects the productivity of basic R&D activities positively through:

\[
\int_{-\infty}^{H(H)} dj HaB(H)H = \frac{\partial B(a_j; H)}{\partial H} > 0; \text{ for this refer to Appendix A. This in turn affects the rental price ratio to wage positively by (25).}
\]

Then \( G_t \), and thus income level and growth responds positively by Footnote 17, establishing endogenous growth.

#### 1. A Smaller Gap from the Technology Frontier and City Expansion

As an economy’s technology level approaches the technology frontier (i.e., as the technology gap \((\bar{T} - T_{t-1})\) decreases), the curve of (27) shifts right to (27-1), thus increasing \( H \) and \( S \), with the curve of (26) remaining intact as in Figure 1.

From (28), we also infer that \( U \) decreases. Thus, as the distance from the technology frontier \( d \) falls, \( H \), \( S \), and thus \( B(H)H \) increase. Thus, as the distance from the technology frontier falls, technology creation activities increase while technology adoption activities decrease. In addition, the urban rental price ratio to wage increases by (25). A smaller technology gap engenders economic growth, if the effect of the increased productivity of basic R&D activities is greater than the cost arising from the smaller gap from the technology frontier.

The magnitude of the effect of a decrease in \( d \) on \( H \) and \( S \) depends on whether city size increases so as to harbor the increased number of highly skilled workers. This is because \( B(H)H \) increases more if the city size increases with an increase in \( H \), than otherwise.\(^{28}\) This can be easily analyzed by using Figure 1. E1 represents the

---

\(^{28}\) Refer to Footnote 14. When the city expands, we have \( B(H^{e})H^{e} = \int_{a_{\bar{H}}}^{a_{H}} B(a_j; H^{e}) dj = \int_{a_{H}}^{a_{\bar{H}}} B(a_j; H^{e}) dj \), where the superscript ‘\( e \)’ represents ‘expanded new city’ and \( H^{e} > H \Rightarrow a_{\bar{H}}^{e} > a_{\bar{H}} \). In contrast, when it does not, the
equilibrium of the case without increasing city size (i.e., with the increased fraction of highly skilled workers residing outside the city), while E2 the equilibrium of the case with increasing city size (with the increased fraction residing within the expanded city).

An increase in $B(H)H$ in (26), caused by an increase in city size, increases $S$ for any given $H$ (the number of highly skilled workers), thus shifting (26) to (26') in Figure 1. Also an increase in $B(H)H$ in (27) increases $S$ for any given $H$ (the number of highly skilled workers), thus shifting (27) to (27'). And we can easily infer that a decrease in $d$ shifts (27) and (27') left to (27-1) and (27'-1), respectively, as in Figure 1. Note that at the initial equilibrium value of $H$ (with the initial size of the city that can harbor $H$), (27) and (27') have the same value of $S$, as E3 ($S', H$) in Figure 1 indicates.

Thus, if the city can be expanded such that the increased supply of highly skilled workers can reside inside it, in response to a decrease in $d$, $S$ increases more than if the city size does not increase. However, the effect of expanding the city size on $H$ (the number of highly skilled workers) is not clear. It is because the marginal worker’s entire benefit of an increase in the productivity of basic R&D activities as a result of the increased city size, goes to landowners by the relationship of (24).

These effects suggest that when the distance from the technology frontier decreases, economic growth increases more with a corresponding increase in city size than without it, because the productivity of basic R&D activities and the supply of $S$ increase more in the former case. In other words, a decrease in $d$ transforms the economy from technology adoption based to technology creation based more rapidly with a corresponding increase in city size. However, to increase the city size appropriately, government intervention is necessary, because urbanization involves coordination problems due to the public good property of infrastructure construction of communication and transportation, and network externalities of knowledge spillovers.

2. Urban Rent Subsidy

If landowners’ rental income can be shared with highly skilled workers, for example, by taxing landowners’ rental income and subsidizing rents for highly skilled workers, then the economy can grow faster by increasing the supply of $H$ and the productivity of basic R&D activities. To simplify the exercise, assume that the landowner’s above expression will be replaced by $B(H^*)H^* = \int_{a_{ii}}^{a_i} B(a_i; H) dj + \int_{a_{ii}}^{a_{ii}} B(0) dj$, where the superscript ‘$n$’ represents ‘not expanded city’ and $H^* > H \Rightarrow a^*_{ii} > a^{**}_{ii}$.
bargaining power is unity, \( \psi = 1 \) and the fraction \( \eta \) of the rent is subsidized.

Here, the rent is determined by the relationship of

\[
R(a^*_H; \eta) = (1 - \eta) \left( 1 - \frac{C_H}{n(a^*_H)} \right) \left[ w(a^*_H) - w(0) \right]
\]

(29)

\[
= (1 - \eta) \left( 1 - \frac{C_H}{n(a^*_H)} \right) \left[ B(a^*_H; H) - B(0) \right] \cdot G_{c_i}, \pi
\]

\[
= (1 - \eta) \left( 1 - \frac{C_H}{n(a^*_H)} \right) \frac{B(a^*_H; H) - B(0)}{\alpha - 1} \frac{S}{BH} w(S)
\]

where \( \eta \) represents the fraction of the rent subsidized for highly skilled workers. (29) can be rearranged to the ratio of rent to wage:

\[
\frac{R(a^*_H; \eta)}{1 - \frac{C_H}{n(a^*_H)} w(a^*_H)} = (1 - \eta)(1 - w(0))/w(a^*_H) = (1 - \eta) \left( 1 - \frac{B(0)}{B(a^*_H; H)} \right)
\]

(30)

Then, (23) and (26) can be rewritten as (31) and (32), respectively:

\[
\left( 1 - \frac{C_H}{n(a^*_H)} \right) w(a^*_H) - R(a^*_H; \eta) = \left( 1 - \frac{C_H}{n(a^*_H)} \right) \left[ (1 - \eta)w(0) + \eta w(a^*_H) \right] = w(S)
\]

(31)

\[
\Rightarrow a_j > n^{-1} \left( C_H \frac{(\eta B(a^*_H; H) + (1 - \eta)B(0))S}{(\eta B(a^*_H; H) + (1 - \eta)B(0))S - (\alpha - 1)(B(H)H)} \right) = a^*_H
\]

(32)

\[
H = 1 - a^*_H = 1 - n^{-1} \left( C_H \frac{(\eta B(a^*_H; H) + (1 - \eta)B(0))S}{(\eta B(a^*_H; H) + (1 - \eta)B(0))S - (\alpha - 1)(B(H)H)} \right),
\]

From (32), we can easily infer that an increase in \( \eta \) lowers \( S \), when \( H \) is fixed. Thus, an increase in \( \eta \) shifts the curve of (32) left to (32-2) in Figure 2, increasing \( H \) and lowering \( S \). In contrast, (27) implies that for any given \( H \), an increase in \( \eta \) does not affect the curve of (27). In addition, (28) implies that both \( H \) and \( S \) go up whereas \( U \) falls. Thus, an increase in \( \eta \) shifts the curve of (32) left to (32-2) in Figure 2, without affecting (27), which leads to greater \( H \) and hence economic growth, and lower \( S \) and
In an extreme case of \( \eta = 1 \), where the entire rents are subsidized for highly skilled workers, city size and economic growth are maximized. This is because landowners in this model economy are seeking rents only, not affecting any economic productivity and growth.

While simplistic, this exercise suggests that by implementing regional policies (e.g., controlling urban rents) that are designed to internalize agglomeration externalities, government can optimize the creation and sharing of knowledge spillovers within cities. It is notable that along with the conventional role of mitigating negative externalities arising from infrastructure congestion and pollution, government needs to view urban rental control from the perspective of facilitating agglomeration effects.

3. Advancement in Information Technology

Advancements in IT increase both \( B(a_j; H) \) and \( B(0) \) for all \( a_j \), e.g., through decreases in the geographic attenuation rate, shift (27) right in Figure 3. They also shift (26) right, if the ratio \( B(a^*_{ij}; H)/B(0) \) rises (i.e., if the induced increase in knowledge spillovers within the city is greater than that outside the city), while they shift left if \( B(a^*_{ij}; H)/B(0) \) falls. Thus, if \( B(a^*_{ij}; H)/B(0) \) increases, advancements in IT increase \( S \), while their effect on \( H \) is not definitive. And if \( B(a^*_{ij}; H)/B(0) \) falls, advancements in IT increase \( H \), while the effect on \( S \) is uncertain.

However, in any case, advancements in IT increase income level and growth by Footnote 17, and their effect on the rental price ratio to wage depends on the relative increase in \( B(0) \) to \( B(a^*_{ij}; H) \) by (25).

The intuition is this. If \( B(0) \) increases more than \( B(a^*_{ij}; H) \) through advancements in IT – perhaps the usual case, because residing outside the city can adopt increased knowledge spillovers more than residing within it, then (24) implies that the rent in the city will fall, resulting in an increase in \( H \) and thus city size. In contrast, if \( B(a^*_{ij}; H) \) increases more than \( B(0) \) through advancements in IT, because residing within the city can adopt relatively more of knowledge spillovers than residing outside it, then (24) implies that the rent in the city will increase, resulting in an ambiguous effect on \( H \) and city size.

It may sound counterintuitive that when knowledge spillovers occur more actively outside the city than within the city, the equilibrium size of highly skilled workers increases.
This is simply because it reduces the urban rent. Note here that the equilibrium rent is determined by the compensating differential between residing within the city and outside the city, especially for marginal workers. Considering these, the causality is: When the increase in knowledge spillovers outside the city becomes relatively greater than that within the city, the compensating differential decreases. Lower compensating differential leads to lower rents, which in turn increases the supply of highly skilled workers. Analyses of other interesting comparative statics are presented in Appendix B.

V. Summary and Conclusion
The paper accounts for the observed correlations among urban agglomeration, skill upgrading, and fast growth in catching-up economies. To address this, we study how urban agglomeration interacts and evolves with the structure of human capital and R&D investment and economic growth, as an economy gets closer to the world technology frontier. As the technology gap narrows, more skilled workers are demanded more to increase basic and development R&D activities of the technology creation sector, respectively. This is because technology creation becomes more profitable than technology adoption with a narrower distance from the technology frontier.

In addition, clustering highly skilled workers through urban agglomeration will increase their productivity of basic R&D activities and thus economic growth, by helping them benefit from knowledge spillovers. This is based on the idea that more creative basic R&D activities benefit more positively from knowledge spillovers, compared to other less creative activities. Thus, this leads to the result that urbanization and basic R&D activities mutually reinforce each other.

Aside from accounting for the observed correlations, our model has the following results. First, as the distance from the technology frontier narrows, city size, and the rental price ratio to wage increase by raising the demand for highly skilled and skilled workers. This lowers the demand for less skilled workers and thus technology adoption activities. Second, urban rental control (e.g., landowners’ rental income is shared with highly skilled workers by subsidizing rents for the latter) helps economy grow faster by increasing the supply of highly skilled workers, city size, and the productivity of basic R&D activities. Last, IT advancement boosts city size, and economic growth.

Future research would include elaborating the micro mechanism of knowledge
spillovers such that we can apply simulation and calibration exercises to explain related empirical stylized facts. For example, we can test theoretical implications about the equilibrium rental price scheme by fitting the model with data. Also, we can introduce additional dynamic features into the model by including human capital and physical capital accumulation. This will make the model more realistic and suitable for additional empirical studies.
Appendix A: The Micro-mechanism of $B(a; H)$ and Determination of the Equilibrium Rent

Assume the following spatial sorting that highly skilled workers live in a city in descending order of their ability from its center to the periphery, and that higher ability workers create a higher level of information spillovers. Then, a worker with ability $a$ residing at the equilibrium location $x \in [-H/2, H/2]$ (see Figure A1), whose equilibrium distance from the city’s center equals $z = |x| = (1 - a)/2$, creates knowledge spillovers per unit of time:

$$I(z) = I(0) \exp(-\theta z)$$

$$= I(0) \exp\left(-\frac{\theta(1 - a)}{2}\right), \text{ with } z = \frac{1-a}{2} \text{ in equilibrium},$$

where $I(0)$ represents the amount of knowledge spillovers per unit of time created by a worker with ability $a = 1$ residing at $z = 0$, $\theta$ is a scale parameter for “ideas creation,” and $z$ represents the “distance” from the city’s center.

Thus, this expression implies that the more remote from the center, the amount of knowledge spillovers that one can create per unit of time will be smaller, because this worker’s ability gets lower in equilibrium.

A worker, with ability $a$ residing at location $x$ in the city, adopts knowledge spillovers created by all workers in the city with the “absorptive capacity” $c(a)$. However, with the wider distance $t$ between the sender and the receiver of information (knowledge spillovers), the less information the latter can obtain, since information attenuates more by a factor of $\exp(-\delta t)$ with a positive geographic attenuation rate $\delta$.

Note here that the capacity of each location’s public hub which manages the information flows equals the information absorbing capacity of its residents in equilibrium.

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29 The “social nature of knowledge creation” in our model is different from that of Alvarez et al. (2008), Lucas and Moll (2011) and several others. Lucas’ mechanism depends mostly on the process of one agent’s social activities of meeting people and comparing their technologies to choose the most efficient technology. But in our model, the mechanism is basically accumulating various ideas from various people, which creates a more efficient technology through new combinations of them. Our mechanism highlights the spirit that “creativity comes from novel combination and association of various ideas.” This is consistent with the following quote from Glassman (2009).

“Francis H. Cartier, “There is only one way in which a person acquires a new idea: by the combination or association of two or more ideas he already had into a new juxtaposition in such a manner as previously aware” (p. 48). Jacques Hadamard, a famous mathematician who proved chaotic theory, “that invention or discovery, be it in mathematics or anywhere else, takes place by combining ideas” (p.49). …Jack Foster (1996) argues these definitions all highlight new ideas as a recombination of elements of others ideas.”
Given these, in equilibrium, the productivity of basic R&D activities of the worker with ability \( a \) and at location \( x \in [0, H/2] \) is described by the following.\(^{30}\) To explain incentive compatibility conditions, we express the value \( V(a, x; H) \) for those whose ability is below the equilibrium ability at location \( x \) with \( a_x \equiv 1 - 2x \geq a \):

\[
V(a, x; H) = B(0) + c(a) \left\{ \int_0^x I(0) \exp(-\theta z) \exp(-\delta(x - z)) dz \right. \\
+ \int_x^H I(0) \exp(-\theta z) \exp(-\delta(x - z)) dz \\
+ \int_0^H I(0) \exp(-\theta z) \exp(-\delta(x + z)) dz \right\}
\]

where \( \delta \) represents the geographic attenuation rate of information, and \( c(a) \) is the absorptive capacity of a worker with ability \( a \), with \( c'(a) > 0 \) and \( c(0) = 0 \). \( c(0) = 0 \) implies that \( V(0, x; H) = B(0; H) = B(0) \). We will refer to the parenthesis part as \( M \) for future reference. The geographic attenuation rate also captures the cost of infrastructure congestion and pollution as city size increases. And \( B(0) \) represents the productivity of basic R&D activities without any knowledge spillovers outside the city.

The counterpart for those above the equilibrium ability at location \( x \) with \( a_x \equiv 1 - 2x < a \):

\[
V(a, x; H) = V(a_x, x; H) \\
= B(0) + c(a_x) \left\{ \int_0^x I(0) \exp(-\theta z) \exp(-\delta(x - z)) dz \right. \\
+ \int_x^H I(0) \exp(-\theta z) \exp(-\delta(x - z)) dz \\
+ \int_0^H I(0) \exp(-\theta z) \exp(-\delta(x + z)) dz \right\}
\]

Note that \( V(a, x; H) \) for those with \( a_x \equiv 1 - 2x < a \), i.e., those with “overqualified at location \( x \)” can extract knowledge spillovers at the capacity of location \( x \), \( c(a_x) \), because limitations in location-specific information processing capacity restrict individuals’ ability to extract information.

Simple algebra solves individual terms of (A2) as

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\(^{30}\) In equilibrium, \( x = \frac{1-a}{2} \) and \( V(a, \frac{1-a}{2}; H) = B(a; H) \).
\[ \int_0^x I(0) \exp(-θx) \exp(-δ(x-z))dz = \int_0^x I(0) \exp(-δx - (θ - δ)z)dz \]
\[ = I(0) \exp(-δx) \int_0^x \exp(-(θ - δ)z)dz \]
\[ = I(0) \exp(-δx) \frac{1}{θ - δ} \left[ 1 - \exp(-(θ - δ)x) \right] \]
\[ = I(0) \frac{1}{θ - δ} \left[ \exp(-δx) - \exp(-θx) \right] \]

(A3)

\[ \int_0^x I(0) \exp(-θx) \exp(-δ(z-x))dz = I(0) \exp(-δx) \int_0^x \exp(-(θ + δ)z)dz \]
\[ = I(0) \exp(-δx) \frac{1}{θ + δ} \left\{ \exp(-(θ + δ)x) - \exp\left(- \frac{H(θ + δ)}{2}\right) \right\} \]

(A4)

\[ \int_0^x I(0) \exp(-θx) \exp(-δ(x+z))dz = I(0) \exp(-δx) \int_0^x \exp(-(θ + δ)z)dz \]
\[ = I(0) \exp(-δx) \frac{1}{θ + δ} \left\{ 1 - \exp\left(- \frac{H(θ + δ)}{2}\right) \right\} \]

(A5)

Thus, combining individual terms, we have:

(A6)
\[ V(a, x; H) = c(a)I(0) \left\{ \frac{-1}{θ + δ} \exp\left(-(θ + δ)\frac{H}{2}\right) (\exp(-δx) + \exp(δx)) \right. \]
\[ + \frac{2}{θ^2 - δ^2} (θ \exp(-δx) - δ \exp(-θx)) \left\} + B(0) \quad \text{for} \quad a_x \equiv 1 - 2x \geq a; \]
\[ V(a, x; H) = c(a_x)I(0) \left\{ \frac{-1}{θ + δ} \exp\left(-(θ + δ)\frac{H}{2}\right) (\exp(-δx) + \exp(δx)) \right. \]
\[ + \frac{2}{θ^2 - δ^2} (θ \exp(-δx) - δ \exp(-θx)) \left\} + B(0) \quad \text{for} \quad a_x \equiv 1 - 2x < a; \]

Reminding that in equilibrium \( V(a, \frac{1-a}{2}; H) = B(a: H) \) or \( V(1-2x, x: H) = B(1-2x: H) \) with \( x = \frac{1-a}{2} \), we can easily show that the productivity \( B(a; H) \) increases.
in ability \( a \) and in city size \( H \), while it decreases in \( \delta \) and \( \theta \). From (A6), we can easily derive that
\[
\frac{\partial}{\partial x} V(a, x; H) < 0 \quad \text{and} \quad \frac{\partial^2}{\partial x^2} V(a, x; H) < 0.
\]

Thus, (A6) implies that the productivity of basic R&D activities of the worker with ability \( a \) and at location \( x \) consists of two parts: (i) the worker’s “absorptive capacity” \( c(a) \) with \( c'(a) > 0 \), and (ii) the total amount of information flows at location \( x \). Using (A2), we denote the latter part as \( M \) as defined above:

\[
M(x; H) \equiv \left[ V(a, x; H) - B(0) \right] / c(a)
\]

(A7)

\[
= I(0) \left\{ \frac{-1}{\theta + \delta} \exp \left( - (\theta + \delta) \frac{H}{2} \right) \left( \exp(-\delta c) + \exp(\delta c) \right) \right. \\
+ \frac{2}{\theta^2 - \delta^2} \left( \theta \exp(-\delta c) - \delta \exp(-\theta c) \right) \right\}
\]

We easily infer that \( M(x; H) \) (thus, \( V(a, x; H) \)) decreases in \( x \), \( \delta \), and \( \theta \), and increases in \( H \). We can also infer that \( \frac{\partial^2}{\partial x^2} M(x; H) < 0 \) (thus, \( \frac{\partial^2}{\partial x^2} V(a, x; H) < 0 \)). Now, we characterize the equilibrium rent \( R(x) \) for location \( x \).

The following incentive compatibility conditions must be satisfied for the equilibrium allocation of abilities over locations, that highly skilled workers are aligned in a city in descending order of the magnitude of their ability from its center to the outside, to be in equilibrium. If workers with ability \( a \) migrate from their equilibrium location \( x^* = (1-a)/2 \) to another location \( x \) closer to the center with a higher rent, in equilibrium, the benefit of the increased wage rate caused by the increased knowledge spillovers must be dominated by the increased rental cost. Using (21), for all \( x < x^* \in [0, H/2] \) this condition is described by:

\[
\frac{S}{\alpha - 1} \frac{V(a, x; H) - V(a, x^*; H)}{B(H)H} w(S) = \frac{S}{\alpha - 1} \frac{V(1-2x^*, x; H) - V(1-2x^*, x^*; H)}{B(H)H} w(S)
\]

(A8)

\[
< R(1-2x) - R(1-2x^*)
\]

\[
= \psi \frac{S}{\alpha - 1} \frac{V(1-2x, x; H) - V(1-2x^*, x^*; H)}{B(H)H} w(S)
\]
Note that this worker’s original ability \( a = 1 - 2x^* \) is used in this calculation. We assume (A8) is satisfied.

In addition, if workers with ability \( a \) migrate, from their equilibrium location \( x^* = \frac{1-a}{2} \), to another location \( x \) farther away from the center with a lower rent, in equilibrium the benefit of the decreased rental cost must be dominated by the decreased wage rate caused by the decreased knowledge spillovers for all \( x > x^* \in [0, H/2] \):

\[
\frac{S}{\alpha - 1} \frac{V(a, x; H) - V(a, x^*; H)}{B(H)H} w(S) = \frac{S}{\alpha - 1} \frac{V(1-2x, x; H) - V(1-2x^*, x^*; H)}{B(H)H} w(S) < R(1-2x) - R(1-2x^*)
\]

\[
= \psi \frac{S}{\alpha - 1} \frac{V(1-2x, x; H) - V(1-2x^*, x^*; H)}{B(H)H} w(S)
\]

Note that in this migration the original ability of a worker at \( x^* \), \( a = 1 - 2x^* \), is no longer applicable and instead the migrating region’s ability \( a = 1 - 2x \) is used in this calculation. It is obvious that (A9) holds true.

We have the following implications about the equilibrium rent scheme for various locations. First, the rent increases as rapidly as the equilibrium wage of each location as the location moves to the city’s center. And for the incentive compatibility conditions to be satisfied, we need the limited capacity of the public hub that prevents workers from migrating to lower ability locations. Second, as city size increases, the urban rent for all locations in the city rises, because productivities of all workers in the city rise.
Figure A1. A City with Size $H$

Figure A2. Wage and Rent for Locations with $\psi = 1$
Appendix B: Other Comparative Statics

B.1. An Increase in Population Density

The paper assumes that the population density is fixed at one. However, if we set the population density to be $p$, then the information attenuation rate $\delta$, determining the productivity of basic R&D activities in the model presented in Appendix A, has only to be replaced with $\delta/p$ for obvious reasons.

In this extended model, an increase in the population density enhances the level of knowledge spillovers and thus $B(H)H$ by reducing the information attenuation rate $\delta$, increasing the productivity of basic R&D activities, the number of skilled workers, economic growth, and the rental price ratio to wage. It is because the increase in the population density shifts both curves of (26) and (27) right by increasing $B(H)H$ in Figure 3.

B.2. An Increase in the Efficiency of a City

With an increase in the efficiency of a city, (26) and (27) shift right to (26-1) and (27-1) respectively in Figure 3, increasing $S$ and economic growth (and $H$ can increase or decrease). This is because with an increase in the efficiency of a city, $B(H)H$ in (26) and (27) increases. In addition, (28) implies that as $B(H)H$ increases, $U$ decreases, increasing $S + H$. These imply the followings.

As a city becomes more efficient especially in creating and sharing information, knowledge spillovers increase among highly skilled workers, and thus, their productivity of basic R&D activities also increases, resulting in an increase in their rental price ratio to wage in the city as a result of an increase in $B(H)H$ in (25). However, the wage net of the rent of workers with ability $a^*_H$ (marginal workers) within the city remain identical with the wage outside the city. This is because the marginal worker’s entire benefit of residing in the city accrues to the owners of immobile factor, land, thus increasing his rent through the relationship of (24).

B.3 An increase in the ratio $\frac{\kappa A_{C,-1}}{A_{D,-1}}$ shifts the curve of (27) right to (27-1) in Figure 3,

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31 An increase in the efficiency of a city is represented, for example, by lowering the geographical attenuation rate. Lowering the geographical attenuation rate leads to a higher value of $B(H)H$. Thus in our model, more open and creative cities can be characterized as having low geographical attenuation rates and high values of $B(H)H$. 
thus increasing $H$ and $S$. Thus, $U$ decreases. Thus, it increases city size, the productivity of basic R&D activities, the rental price ratio to wage, and economic growth.

**B.4. An increase in the productivity of the education system for highly skilled workers** (a decrease in $C_{HH}$) shifts the curve of (23) left to (26-2) in Figure 3, thus raising $H$ and lowering $S$. (28) implies that $U$ decreases. Thus, it increases city size, the productivity of basic R&D activities, the rental price ratio to wage, and economic growth.

**B.5. An increase in the productivity of the education system for skilled workers** (a decrease in $C_S$) shifts the curve of (27) right to (27-1) in Figure 3, thus raising $H$ and $S$. Thus $U$ decreases. Thus, it increases city size, the productivity of basic R&D activities, the rental price ratio to wage, and economic growth.

**B.6. An increase in the productivity of basic R&D activities for highly skilled workers** (an increase in $B$) shifts the curve of (26) left to (26-2) and the curve of (27) right to (27-1) in Figure 3, thus increasing $H$ still further. And the effect on $S$ depends on the elasticities of these two graphs. (28) implies that $U$ decreases. Thus, it increases city size, the rental price ratio to wage, and economic growth.
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Figure 1. Comparative Statics: a Decrease in the Technology Distance $d$

Figure 2. Comparative Statics: Rent Subsidies
Figure 3. Other Comparative Statics