The Choice of Technology and Economic Geography

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4 December 2021

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Abstract

Empirical evidence shows that firms located in regions with larger population size are on average larger and more productive. To explain this empirical observation, firms producing intermediate goods are assumed to choose their technologies with different levels of fixed and marginal costs. In this general equilibrium model of economic geography, intermediate good producers engage in oligopolistic competition. The model is tractable and leads to interesting and analytical results. An intermediate good producer in the region with a higher population produces a higher level of output and has a lower marginal cost of production regardless of the existence of regional trade. With regional trade, if a worker moves from the region with a lower number of workers to the region with a higher number of workers, intermediate good producers in both regions choose less advanced technologies.

Keywords: Technology choice, economic geography, international trade, increasing returns, oligopoly

JEL Classification Numbers: F12, R12, L13, D43, O14

1. Introduction

Empirical evidence shows that firms located in larger metropolitan areas are on average larger and more productive. For example, Holmes and Stevens (2002) find that manufacturing plants located in areas where an industry concentrates are substantially larger than those in the same industry outside such areas. Using U. S. data, Wheeler (2006) shows that average plant size increases significantly with an industry's employment in a metropolitan area. Using Chinese data, Li, Lu, and Wu (2012) establish a positive relationship between industry agglomeration and firm size. Also, large plants on average are more productive (Oi and Idson, 1999).

The size and productivity of a firm are not exogenously given, and they are likely to be affected by a firm's technology, which will be determined by fundamental factors such as population size in a region (Combes et al., 2012).[1] That is, firms choose their technologies based on their levels of outputs, which are affected by regional population sizes. There are numerous examples of firms' choices of technologies. First, Porter (1990, p. 97) discusses choices of printers

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[1] There are two main explanations that on average firms are more productive in larger cities: firm selection because a larger market size leads to a higher degree of competition and less efficient firms would be forced to exit, and agglomeration economies. Using French data, Combes et al. (2012) find that firm selection cannot explain spatial productivity differences.

by firms. There are three types of printers, and the most expensive one is the fastest and is suitable for large volume printing such as printing newspapers. The costs of purchasing printers are fixed costs and an increase in the level of fixed costs leads to a decrease in the marginal cost of printing. Second, Prendergast (1990) discusses the tradeoff between fixed and marginal costs in three industries: nuts and bolts, iron founding, and machine tools. In those industries, technologies with higher fixed costs have lower marginal costs of production. Prendergast shows that a firm's output determines its choice of technology: a higher level of output leads to the adoption of technologies with higher fixed costs of production. Finally, Levinson (2006) discusses the adoption of containers and the choice of technology in the transportation sector. The adoption of containers was one of the most important innovations in the transportation sector in the twentieth century. Adoption of containers began in the 1950s. At that time, the loading and unloading of cargos were handled by longshoremen and were labor-intensive. With high wage rates, marginal costs were high. Because specially designed cranes, containerships, and container ports had to be built, the adoption of containers led to sharp rises in fixed costs in the transportation sector. However, compared with the technology of using longshoremen to load and unload cargos, marginal costs of loading and unloading decreased sharply.

In models of economic geography, it is frequently assumed that firms in different regions use the same technology by specifying that firms have the same fixed and marginal costs of production. Incorporating a firm's technology choice will be useful in explaining the empirical evidence that firms in larger cities are on average more productive. One interesting question about technology choice is the following. Suppose a worker moves from a region with a lower population to a region with a higher population. After this labor movement, firms in the two regions may adjust their technologies. Will this labor mobility lead to an increase in the degree of technological difference between the two regions in the sense that firms in the region with a higher population choose more advanced technologies while those in the region with a lower population choose less advanced technologies? The wage rate in a region can be directly related to a firm's technology and a larger technology gap between regions may induce a larger wage gap. If this larger wage gap increases a worker's utility in the region with a higher population relatively, remaining workers in the region with a lower population have incentives to move to the region with a higher population. That is, will the choice of technology work as a channel for the concentration of economic activities?

In this paper, we show that the incorporation of technology choice into a general equilibrium model of economic geography can explain the empirical observation that firms located in areas with large population size are on average larger and more productive. In this model, farmers and workers live in two regions. Individuals consume an agricultural good and a manufactured good. The manufactured good is produced by intermediate goods and intermediate good producers choose technologies to maximize their profits. Different technologies differ in their fixed and marginal costs. Like Spencer and Brander (1983), Venables (1985), Qiu and Zhou (2007), Chen and Shieh (2011), and Neary (2016), intermediate good producers engage in oligopolistic competition.[2] The motivation of oligopoly as the type of market structure is as follows. When firms engage in oligopolistic competition, the number of firms producing the same intermediate input can be affected by fundamental factors like population size. Oligopoly as a type of market structure can be used to address how a firm's level of output changes with fundamental factors (Neary, 2001). When a firm's output changes, its level of technology can change correspondingly. Thus, a firm's technology choice can be conveniently addressed when firms engage in oligopolistic competition.

With regional trade, we show that the region with a higher number of workers (region 1) exports the manufactured good to the other region (region 2) and imports the agricultural good. Consistent with empirical observation, we show that an intermediate good producer in the region with a higher number of workers produces a higher level of output and have a lower marginal cost of production regardless of the existence of regional trade or not.

Interestingly, the incorporation of the choice of technology does not increase the wage gap or technology gap between the two regions. If a worker moves from the region with a lower number of workers to the other one, surprisingly intermediate good producers in both regions choose less advanced technologies, but the wage ratio between the two regions will not change. A firm's technology choice is determined by its level of output, which depends on market size (Zhou, 2004). Since market for the manufactured good is integrated for the two regions, market size is a weighted average of population of the two regions. When a worker moves from region 2 to region 1, market size decreases and the "total effective output" of the manufactured good (which is the sum of

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[2] Oligopoly has been an important type of market structure for developed countries such as the United States since the Second Industrial Revolution because the existence of significant fixed costs in production leads to increasing returns to scale (Chandler, 1990). Thus, large firms have cost advantages over small firms and perfect competition will not prevail.

regional outputs weighted by transportation costs) from the two regions decreases, thus intermediate good producers choose less advanced technologies. The wage ratio will not change because the number of intermediate good producers will adjust in both regions. When region 1 has a higher number of workers, the number of intermediate good producers increases in this region. When region 2 has a lower number of workers, the number of intermediate good producers in region 2 decreases. Overall, worker mobility will not widen the technology difference and the wage ratio between the two regions. That is, while the choice of technology as a channel of industry concentration seems intuitive, how this mechanism works is not as straightforward as we have expected.

In a seminal paper, Krugman (1991) studies a model of economic geography in which firms engage in monopolistic competition. Nocco (2005) introduces differences in technologies used by firms located at different regions and studies how these differences may evolve over time according to the level of international economic integration. This line of literature is synthesized in Fujita, Krugman and Venables (1999). Models of economic geography in which firms engage in oligopolistic competition have been studied by Combes (1997), Belleflamme, Picard, and Thisse (2000), Zhou (2007), Combes and Lafourcade (2011), Dewit, Leahy, and Montagna (2013).[3] This paper contributes to the literature by incorporating technology choice into a general equilibrium model of economic geography in which firms engage in oligopolistic competition.

The plan of the paper is as follows. Section 2 specifies the model and establishes the equilibrium when there is no regional trade. Except that intermediate good producers engage in oligopolistic competition rather than monopolistic competition and choose technologies, the specifications of this model and the questions addressed follow those in Krugman (1991) closely. Section 3 studies whether the equilibrium with equal distribution of workers in the two regions without regional trade is stable. Section 4 revisits the equilibrium when there is regional trade. Section 5 examines the impact of worker movement under regional trade. Section 6 concludes. The Appendix contains the proofs of all propositions.

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[3] Combes (1997) assumes that markets for manufactured goods are segregated. Belleflamme, Picard, and Thisse (2000) allow for technological spillovers among firms. Zhou (2007) assumes that markets for manufactured goods are integrated. Combes and Lafourcade (2011) study a multi-region and multi-industry model. Dewit, Leahy, and Montagna (2013) address the use of labor standard as a commitment device when strategic interaction among firms is important.

2. Regions in autarky

There are two regions: region 1 and region 2. Subscripts of variables are used to denote regions. A region has farmers and may have workers. Farmers are specific to the agricultural sector and cannot move between the regions (Krugman, 1991). All farmers and workers in the two regions have the same preferences. Also, the two regions have access to the same set of agricultural and manufacturing technologies. In this section, we study the equilibrium when there is no regional trade. We focus on the study of region 1. First, we study a consumer's utility maximization. Second, we examine profit maximization of a final good producer and that of an intermediate good producer. Third, we set up market clearing conditions, including labor market and goods markets clearance. Finally, we establish the autarky equilibrium.

2.1. Utility maximization

A consumer derives utility from two goods: an agricultural good and a manufactured good. A consumer's consumption of the agricultural good is C^A and her consumption of the manufactured good is C^M. For the constant $\alpha \in (0, 1)$, her utility function is $U = (C^A)^\alpha (C^M)^{1-\alpha}$. With this homothetic utility function, utility maximization requires that a consumer spends α percent of income on the agricultural good and 1-α percent of income on the manufactured good.

2.2. The agricultural sector

The agricultural good is produced by farmers. The number of farmers in region 1 is T_1, which is exogenously given. There are constant returns to scale in the agricultural sector. Without loss of generality, each farmer in the agricultural sector produces one unit of the agricultural good. Thus, the level of agricultural output in region 1 is T_1. The agricultural good is used as the numeraire: $p^A = 1$. With this normalization, the income of a farmer is one.

2.3. The manufacturing sector

The manufactured good is produced by combining a continuum of intermediate goods indexed by a number $\omega \in [0,1]$ (He and Yu, 2015; Tabuchi, Thisse, and Zhu, 2018).[4] The price of an intermediate good ω in region 1 is $p_1(\omega)$. All intermediate goods have the same costs of

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[4] Tabuchi, Thisse and Zhu (2018) analyze how reductions due to technological progress in the costs of producing and trading goods interact with the various costs borne by migrants who can be mobile between regions.

production and enter the production of the manufactured good in a symmetric way.[5] Except the usage of intermediate goods, the manufactured good is produced without incurring any additional cost. Let δ denote a positive constant not smaller than one. If the amount of intermediate good ω used in the production of the manufactured good is $q^M(\omega)$, then the manufactured output is $\left(\int_0^1 q^M(\omega)^{\frac{\delta-1}{\delta}} d\omega\right)^{\frac{\delta}{\delta-1}}$. The price of the manufactured good is P. Firms producing the manufactured good engage in perfect competition. A firm producing the manufactured good tries

to maximize profit $P\left(\int_0^1 q^M(\omega)^{\frac{\delta-1}{\delta}} d\omega\right)^{\frac{\delta}{\delta-1}} - \int_0^1 p_1(\omega)q^M(\omega)d\omega$. Thus, for i=1, 2 denoting the two regions, a manufactured good producer's profit maximization implies that the elasticity of demand of an intermediate good is constant: $\frac{p_i}{q^M(\omega)} \frac{\partial q^M(\omega)}{\partial p_i} = -\delta$. Also, the relationship between the price of the manufactured good and prices of intermediate inputs is $P = [\int_0^1 p_1(\omega)^{1-\delta} d\varpi]^{\frac{1}{1-\delta}}$.

To produce each intermediate good, there is a continuum of technologies with different fixed and marginal costs indexed by a number $n \in R_+^1$ (Zhou, 2004, 2009, 2019, 2021; Ma, Wang, and Zeng, 2015; Wen and Zhou, 2020). For technology n, fixed costs in terms of labor used are $f(n)$ and marginal cost in terms of labor used is $\beta(n)$. We assume that f and β are twice continuously differentiable functions. To capture the substitution between fixed and marginal costs of production, we assume that a more advanced technology has a higher fixed but a lower marginal cost of production. Specifically, for γ and θ denoting constants belonging to R_+^1, the fixed and marginal costs are

$$f(n) = n^\gamma, \tag{1a}$$

$$\beta(n) = n^{-\theta}. \tag{1b}$$

From equation (1a), when γ increases, fixed costs increase. From equation (1b), when θ increases, marginal cost decreases.

The wage rate in region 1 is w_1. An intermediate good producer's output is x_1, and its profit is $p_1 x_1 - (f_1 + \beta_1 x_1)w_1$. Firms producing the same intermediate good engage in Cournot competition. The number of identical intermediate good producers in region 1 producing

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[5] One purpose of having a continuum of intermediate goods instead of one intermediate good is to eliminate an intermediate good producer's market power in the labor market (Neary, 2016). Otherwise, it can be viewed that there is only one intermediate good.

intermediate good ω is $m_1(\omega)$. An intermediate good producer takes the wage rate as given and chooses its technology and output to maximize its profit. The first order condition for an intermediate good producer's optimal choice of technology is[6]

$$-f'(n_1) - \beta'(n_1)x_1 = 0. \tag{2}$$

From equation (2), it can be shown that an intermediate good producer chooses a more advanced technology when its level of output increases. The intuition is as follows: an increase in output increases the marginal benefit $-\beta'(n_1)x_1$ from adopting a more advanced technology while the marginal cost $-f'(n_1)$ does not change.

The first order condition for an intermediate good producer's optimal output choice requires that

$$p_1\left(1 + \frac{x_1}{p_1}\frac{\partial p_1}{\partial x_1}\right) = \beta_1 w_1. \tag{3}$$

Like Zhou (2007), the elasticity of demand faced by an intermediate good producer is $\frac{p_1 \partial x_1}{x_1 \partial p_1} = -m_1\delta$. Plugging this elasticity into equation (3) yields

$$p_1 = \frac{m_1\delta}{m_1\delta - 1}\beta_1 w_1. \tag{4}$$

Firms enter the intermediate goods sector until the level of profit is zero.[7] Zero profit for an intermediate good producer requires that

$$p_1 x_1 - (f_1 + \beta_1 x_1)w_1 = 0. \tag{5}$$

2.4. Market clearing conditions

For the labor market in region 1, each intermediate good producer demands $f_1 + \beta_1 x_1$ units of labor. Integrating over intermediate goods, total labor demand is $\int_0^1 m_1 (f_1 + \beta_1 x_1)d\omega$. Total labor supply is L_1. The clearance of the labor market in region 1 requires that

$$\int_0^1 m_1 (f_1 + \beta_1 x_1)d\omega = L_1. \tag{6}$$

For the market for the manufactured good in region 1, since a consumer spends 1-α percent of income on the manufactured good and total income in region 1 is $T_1 + w_1 L_1$, total demand for the manufactured good is $(1 - \alpha)(T_1 + w_1 L_1)$. The total value of the supply of the manufactured

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[6] With the specifications of technologies in equations (1a) and (1b), it can be checked that the second order condition for a firm's optimal choice of technology is always satisfied.
[7] For an example that firms engage in Cournot competition with zero profits, see Chen and Shieh (2011).

good equals the value of intermediate goods $\int_0^1 p_1 m_1 x_1 d\omega$. The clearance of the market for the manufactured good in region 1 requires that

$$(1 - \alpha)(T_1 + w_1 L_1) = p_1 m_1 x_1. \tag{7}$$

For the market for the agricultural good in region 1, since a consumer spends α percent of income on the agricultural good and total income in region 1 is $T_1 + w_1 L_1$, total demand for the agricultural good is $\alpha(T_1 + w_1 L_1)$. The value of the total supply of the agricultural good is T_1. The clearance of the market for the agricultural good in region 1 requires that

$$\alpha(T_1 + w_1 L_1) = T_1. \tag{8}$$

2.5. The autarky equilibrium

In this model, we focus on a symmetric equilibrium in which the number of producing firms, the level of output, and the price are the same for all intermediate goods. In a symmetric equilibrium, the price of the manufactured good equals the price of an intermediate good: $P = p_1$. Also, the level of output of the manufactured good equals total output of an intermediate good. Equations (2) and (4)-(8) form a set of six equations defining six variables n_1, m_1, w_1, x_1, p_1, and p^A as functions of exogenous parameters.[8] Since all intermediate goods are symmetric and the total measure of intermediate goods is one, for simplicity we drop the integration operator for intermediate goods in a symmetric equilibrium. An autarky equilibrium is a tuple $(n_1, m_1, w_1, x_1, p_1, p^A)$ satisfying equations (2) and (4)-(8).

Interestingly, we can solve this set of equations explicitly. The following proposition establishes equilibrium values of variables when regions are in autarky.

Proposition 1: In autarky, the equilibrium values of variables are given by

$$w_1 = \frac{(1-\alpha)T_1}{\alpha L_1}, \tag{9}$$

$$m_1 = \frac{\theta + \gamma}{\delta \theta}, \tag{10}$$

$$n_1 = \left[\frac{\delta \theta^2 L_1}{(\theta + \gamma)^2}\right]^{\frac{1}{\gamma}}, \tag{11}$$

$$x_1 = \frac{\gamma}{\theta}\left[\frac{\delta\theta^2 L_1}{(\theta+\gamma)^2}\right]^{\frac{\gamma+\theta}{\gamma}}, \tag{12}$$

$$p_1 = \frac{(1-\alpha)(\theta+\gamma)^{\frac{\gamma+2\theta}{\gamma}}}{\alpha\gamma\delta^{\frac{\gamma}{\theta}}\theta^{\frac{2\theta}{\gamma}}L_1^{\frac{\gamma+\theta}{\gamma}}}T_1. \tag{13}$$

From equation (11), an intermediate good producer's equilibrium technology increases with population size. This result can be interpreted as the division of labor (the level of technology) increases with the size of the market (Zhou, 2004). Results in Proposition 1 are intuitive. With increasing returns in the intermediate good sector, from equation (12), an intermediate good producer's output increases with the size of the population. With a higher level of output, an intermediate good producer chooses a more advanced technology because the higher fixed cost can be spread over a higher level of output and the average cost of production decreases. With a lower average cost, the price of an intermediate good decreases with population size because the price equals the average cost when firms earn a profit of zero. Those results are consistent with empirical evidence discussed in the Introduction. From equations (10)-(13), when the absolute value of the elasticity of substitution among intermediate goods increases, an intermediate good producer produces more, and the number of intermediate good producers decreases. As intermediate good producers choose more advanced technologies, the price of an intermediate good decreases with the absolute value of the elasticity of substitution among intermediate goods.

3. Worker movement without trade

If the two regions have equal numbers of workers and farmers, since the prices of the agricultural good and the manufactured good will be the same between the two regions, there is no regional trade. The equilibrium with equal distribution of workers between the two regions is stable if a worker's utility decreases with the number of workers in this region. The following proposition addresses the stability of this equilibrium.

Proposition 2: The equilibrium with equal distribution of workers between the two regions is stable if and only if $\theta - \gamma\alpha - \alpha\theta < 0$.

The percentage of income spent on the agricultural good is one of the three key parameters in Krugman (1991). Proposition 2 shows that the equilibrium with equal distribution of workers between the two regions is stable if the percentage of income spent on the agricultural good is sufficiently high. Compared with Zhou (2007), this condition for stability is simpler. In Zhou (2007, p. 926), the ratio between population size and the fixed cost of production is part of the stability condition. With the endogenous choice of technology in this model, the fixed cost is a function of population size. Overall, impact of the fixed cost and population size cancel out and both are absent from the stability condition, while parameters measuring technologies enter this stability condition.

4. Regional trade

We now allow trade between regions. There is no transportation cost for the agricultural good. Thus, the opening of trade will lead to equal price of the agricultural good in the two regions. Transportation costs for the manufactured good are of the iceberg type commonly used in the literature. Specifically, for $1 + t$ units of the manufactured good sent out, only one unit will arrive, where $t \in R_+^1$. We assume that market for the manufactured good in the two regions are integrated. Different from Krugman (1991) and Zhou (2007), the numbers of farmers in the two regions in this paper are not required to be equal.

Total number of workers in the two regions is exogenously given:

$$L_1 + L_2 = L. \tag{14}$$

Without loss of generality, we assume that the number of workers in the manufacturing sector in region 1 is larger than that in region 2: $L_1 > L_2$. We also assume that the number of farmers in region 1 is not larger than that in region 2: $T_1 \leq T_2$. From equation (13), the price of the manufactured good in region 1 before the opening of regional trade will be smaller than that in region 2. With the opening of regional trade, the trade pattern is interindustry trade rather than intraindustry trade: region 1 exports the manufactured good to region 2 and imports the agricultural good from region 2.

If there is regional trade, from the specification of the iceberg transportation technology, the relationship between the prices of the manufactured good in the two regions is

$$p_2 = (1 + t)p_1. \tag{15}$$

Like equation (2), the optimal choice of technology for an intermediate good producer in region 2 requires that

$$-f'(n_2) - \beta'(n_2)x_2 = 0. \tag{2*}$$

Like equation (5), zero profit for an intermediate good producer in region 2 requires that

$$p_2 x_2 - (f_2 + \beta_2 x_2)w_2 = 0. \tag{5*}$$

Like equation (6), the clearance of the labor market for workers in region 2 requires that

$$\int_0^1 m_2 (f_2 + \beta_2 x_2)d\omega = L_2. \tag{6*}$$

For the market for the agricultural good, total demand for the agricultural good from the two regions is $\alpha(T_1 + T_2 + w_1 L_1 + w_2 L_2)$. Total value of the supply of the agricultural good from the two regions is $T_1 + T_2$. The clearance of the market for the agricultural good requires that

$$\alpha(T_1 + T_2 + w_1 L_1 + w_2 L_2) = T_1 + T_2. \tag{16}$$

For the market for the manufactured good in region 1, the amount of exports of the manufactured good from region 1 to region 2 is E. Total demand for the manufactured good in region 1 is $(1 - \alpha)(T_1 + w_1 L_1)$ and total value of the supply of the manufactured good is $p_1(m_1 x_1 - E)$. The clearance of the market for the manufactured good in region 1 requires that

$$(1 - \alpha)(T_1 + w_1 L_1) = p_1(m_1 x_1 - E). \tag{17}$$

For the market for the manufactured good in region 2, the amount of arrived imports of the manufactured good in region 2 is I. Total demand for the manufactured good in region 2 is $(1 - \alpha)(T_2 + w_2 L_2)$ and the total value of the supply of the manufactured good is $p_2(m_2 x_2 + I)$. The clearance of the market for the manufactured good in region 2 requires that

$$(1 - \alpha)(T_2 + w_2 L_2) = p_2(m_2 x_2 + I). \tag{18}$$

With the specification of iceberg transportation cost of the manufactured good, $E = (1 + t)I$. Combining this result with equations (17) and (18) yields

$$(1 - \alpha)(T_1 + T_2 + w_1 L_1 + w_2 L_2) = p_1[m_1 x_1 + (1 + t)m_2 x_2]. \tag{19}$$

For $i = 1,2$, a region i intermediate good producer's optimal choice of output yields $x_i + p_i \frac{\partial x_i}{\partial p_i} - \beta_i w_i = 0$. Like the equilibrium under autarky, it can be shown that $\frac{\partial x_1}{\partial p_1} = -\frac{\delta[m_1 x_1 + (1+t)m_2 x_2]}{p_1}$ and $\frac{\partial x_2}{\partial p_2} = -\frac{\delta[m_1 x_1 + (1+t)m_2 x_2]}{(1+t)p_2}$. Plugging those results into $x_i + p_i \frac{\partial x_i}{\partial p_i} - \beta_i w_i = 0$ yields

$$p_1 \left(1 - \frac{x_1}{\delta[m_1 x_1 + (1+t)m_2 x_2]}\right) = \beta_1 w_1, \tag{20}$$

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$$p_2\left(1 - \frac{(1+t)x_2}{\delta[m_1 x_1 + (1+t)m_2 x_2]}\right) = \beta_2 w_2. \tag{20*}$$

With regional trade, equations (2) and (5)-(6) are still valid. Those equations and equations (2*), (5*), (6*), (15), (19), (20), and (20*) form a system of 11 equations defining a set of 11 variables $n_1, n_2, m_1, m_2, w_1, w_2, x_1, x_2, p_1, p_2,$ and p^A as functions of exogenous parameters. An equilibrium with regional trade is a tuple $(n_1, n_2, m_1, m_2, w_1, w_2, x_1, x_2, p_1, p_2, p^A)$ satisfying equations (2), (2*), (5)-(6), (5*)-(6*), (15), (19), (20), and (20*). Interestingly, while there are 11 equations, we can still solve them explicitly. The results are stated in the following proposition.

Proposition 3: For the equilibrium with regional trade, the equilibrium values of variables are

$$p_1 = \frac{(1-\alpha)(T_1+T_2)(\theta+\gamma)^{\frac{2\theta+\gamma}{\gamma}}}{\alpha\gamma\delta^{\frac{\theta}{\gamma}}\theta^{\frac{2\theta}{\gamma}}\left[L_1+(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2\right]^{\frac{\gamma+\theta}{\gamma}}}. \tag{21}$$

$$w_1 = \frac{(1-\alpha)(T_1+T_2)}{\alpha\left[L_1+(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2\right]}, \tag{22}$$

$$w_2 = \frac{(1-\alpha)(T_1+T_2)}{\alpha\left[L_1+(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2\right]}(1+t)^{\frac{\gamma}{\gamma+\theta}}, \tag{23}$$

$$n_1 = \delta^{\frac{1}{\gamma}}\left(\frac{\theta}{\theta+\gamma}\right)^{\frac{2}{\gamma}}\left[L_1+(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2\right]^{\frac{1}{\gamma}}, \tag{24}$$

$$n_2 = \delta^{\frac{1}{\gamma}}\left(\frac{\theta}{\theta+\gamma}\right)^{\frac{2}{\gamma}}\left[L_1+(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2\right]^{\frac{1}{\gamma}}/(1+t)^{\frac{1}{\gamma+\theta}}, \tag{25}$$

$$x_1 = \gamma\frac{\delta^{\frac{\theta+\gamma}{\gamma}}\theta^{\frac{2\theta+\gamma}{\gamma}}}{(\theta+\gamma)^{\frac{2\theta+2\gamma}{\gamma}}}\left[L_1+(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2\right]^{\frac{\gamma+\theta}{\gamma}}, \tag{26}$$

$$x_2 = \gamma\frac{\delta^{\frac{\theta+\gamma}{\gamma}}\theta^{\frac{2\theta+\gamma}{\gamma}}}{(1+t)(\theta+\gamma)^{\frac{2\theta+2\gamma}{\gamma}}}\left[L_1+(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2\right]^{\frac{\gamma+\theta}{\gamma}}, \tag{27}$$

$$m_1 = \frac{(\theta+\gamma)L_1}{\theta\delta\left[L_1+(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2\right]}, \tag{28}$$

$$m_2 = \frac{(\theta+\gamma)(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2}{\theta\delta\left[L_1+(1+t)^{\frac{\gamma}{\gamma+\theta}}L_2\right]}. \tag{29}$$

Consistent with empirical evidence, from equations (24) and (25), intermediate good producers in region 1 with a higher number of workers choose more advanced technologies and have lower marginal costs of production than those in region 2 with a lower number of workers. From equations (26) and (27), the level of output for an intermediate good producer in region 1 is higher than that in region 2. From equations (28) and (29), the number of intermediate good producers in a region increases with the number of workers in this region and decreases with the number of workers in the other region.

An inspection of Propositions 1 and 3 reveals the following. First, when the number of workers and the number of farmers in region 2 becomes zero, the results in Proposition 3 degenerate to those in Proposition 1. For example, if $L_2 = 0$ and $T_2 = 0$, equation (25) degenerates to equation (13). That is, the autarky equilibrium can be viewed as a special case of regional trade with the numbers of workers and farmers are zero in region 2. Second, when the level of transportation cost is zero, equilibrium values of variables in Proposition 3 will be the same as those in Proposition 1 with the number of farmers of region 1 replaced by the sum of the numbers of farmers and the number of workers in region 1 replaced by the sum of the number of workers in the two regions. That is, the distribution of workers and farmers between the two regions will not affect technology choice in an equilibrium with regional trade if there is no transportation cost. Third, from equations (10), (28), and (29), the sum of firms producing an intermediate input in the two regions in the trade equilibrium is equal to the number of firms producing an intermediate input in the autarky equilibrium. Finally, starting from autarky, both regions will choose more advanced technologies with the opening of regional trade.

5. Worker movement with regional trade

In the equilibrium with regional trade, from equations (25)-(27), a region 2 worker's consumption of the agricultural good is higher while his consumption of the manufactured good is lower than that of a region 1 worker. If the percentage of income spent on the agricultural good is sufficiently low, the level of utility for a region 2 worker will be lower than that of a region 1 worker. Then a worker in region 2 has an incentive to move to region 1.

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Naturally a worker's choice of location is a very interesting issue, we do not study explicitly address this issue here. This can be justified on the ground that in some situations workers may not have this choice such as when *Hukou* system (household registration system) was practiced in China. Under this system, if an individual moves without permission, this individual may not have access to various kinds of benefits such as child care. Also, it can be argued that some factors not included in this model may prevent a worker from moving, such as an individual's preference to stay at hometown. What is the impact on endogenous variables if a worker moves from region 2 to region 1? The following proposition addresses the impact on technology choices by intermediate good producers.

Proposition 4: When a worker moves from region 2 to region 1, intermediate producers in both regions choose less advanced technologies.

Proposition 4 is surprising because we may have expected that intermediate good producers in region 1 choose more advanced technologies when there are more workers in this region. This result is less surprising when we interpret worker movement as relocation of workers between regions, rather than an overall increase in the number of workers. To understand Proposition 4, from equation (2), a firm's equilibrium level of technology increases with its equilibrium level of output, which is endogenously determined by population size (a measure of market size). If we compare equation (24) with (11), technology choice in the equilibrium with regional trade is like that in the autarky equilibrium by replacing population size L_1 with the weighted population of the two regions $L_1 + (1 + t)^{\frac{\gamma}{\gamma+\theta}} L_2$ because markets for the manufactured good is assumed to be integrated. When calculating weighted population, population in region 2 is augmented by $(1 + t)^{\frac{\gamma}{\gamma+\theta}}$ because of the existence of transportation costs. Since $L_1 + (1 + t)^{\frac{\gamma}{\gamma+\theta}} L_2$ is larger than L_1, intermediate good producers choose more advanced technologies in the equilibrium with regional trade. When a worker moves from region 2 to region 1, weighted population of the two regions $L_1 + (1 + t)^{\frac{\gamma}{\gamma+\theta}} L_2$ becomes lower. With a lower market size, from equations (26) and (27), outputs of intermediate good producers are lower, thus intermediate good producers in both regions choose less advanced technologies.

Alternatively, when a worker moves from region 2 to region 1, "total effective output" of the manufactured good defined as the sum of regional outputs weighted by transportation costs decreases. The reasoning is as follows. For a worker in region 2, the level of demand for the manufactured good is $\frac{(1-\alpha)w_2}{p_2}$. Taking account of transportation costs, effective demand for a region 2 worker is $\frac{(1+t)(1-\alpha)w_2}{p_2}$. A region 1 worker's demand for the manufactured good is $\frac{(1-\alpha)w_1}{p_1}$, which is lower than $\frac{(1+t)(1-\alpha)w_2}{p_2}$. That is, total effective output $m_1 x_1 + (1+t)m_2 x_2$ decreases when a worker moves from region 2 to region 1. Because intermediate good producers choose less advanced technologies when output decreases, intermediate good producers in both regions choose less advanced technologies when a worker moves to region 1. For a given number of manufacturing workers L, technologies in both regions are most advanced when the difference in the number of workers between the two regions is just enough for regional trade to be possible (from equations (24) and (25)). Those technologies are more advanced than the one when all workers are concentrated in one region.[9]

Will the choice of technology work as a channel for the concentration of industries? By using Proposition 3 and equation (14) (which shows that the sum of workers in the two regions is a constant), we can get the following results when L_1 increases and L_2 decreases simultaneously. First, from equation (21), the price of the manufactured good in region 1 increases with the number of workers in region 1. The intuition behind this result is that the average cost of producing intermediate goods increases when firms choose less advanced technologies. Second, from equations (22) and (23), the wage rates increase with the number of workers in region 1. This wage increase can be understood from equation (16) which shows that $w_1 L_1 + w_2 L_2$ is a constant because of the assumption of homothetic preferences. When L_2 decreases and L_1 increases by the same amount, because $w_1 < w_2$, $w_1 L_1 + w_2 L_2$ would decrease if w_1 and w_2 do not change. That is, w_1 and w_2 increase to ensure that $w_1 L_1 + w_2 L_2$ does not change. Interestingly, the wage ratio between the two regions is a constant and is affected by the level of transportation cost. When more workers move to region 1, the wage ratio will not change. This constant wage ratio is surprising because with a higher number of workers in region 1 and increasing returns in the manufacturing sector, we may have expected that the wage rate in region 1 will increase relatively

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9 This result can be established by comparing technologies in equations (24) and (25) with those under zero transportation costs and that workers concentrate in region 1.

and that the wage ratio between the two regions will widen. To understand this result that the wage ratio is constant, the number of intermediate good producers in region 2 decreases when workers move out from region 2. Thus, when workers move from region 2 to region 1, intermediate good producers in both regions adjust their technologies. In equilibrium, the ratio of technologies in the two regions is a constant not affected by the distribution of workers between the two regions. Technology determines the marginal units of labor to produce one unit of intermediate good and thus labor productivity. Since the technology ratio does not change, the wage ratio does not change.

The following proposition studies whether the equilibrium that all workers are concentrated in one region is stable.

Proposition 5: The equilibrium that all workers are concentrated in region 1 is stable if and only if

$$n_2 < \frac{\alpha^{\frac{1}{\theta}} L^{\frac{\theta+\gamma}{\gamma\theta}} \delta^{\frac{1}{\gamma}} \theta^{\frac{2}{\gamma}}}{(1+t)^{\frac{\alpha}{\theta}} (\theta+\gamma)^{\frac{2}{\gamma}}}, \tag{30}$$

where n_2 is defined implicitly by

$$\frac{(1+t)(T_1+T_2)(\theta+\gamma)^{\frac{2\theta+\gamma}{\gamma}}}{\delta^{\frac{\theta}{\gamma}} \theta^{\frac{2\theta}{\gamma}} L^{\frac{\gamma+\theta}{\gamma}}} n_2^{\gamma+\theta} - (\gamma+\theta)(1-\alpha)(1+t)^{1-\alpha} \frac{(T_1+T_2)}{L} n_2^{\gamma} - \theta\alpha T_2 = 0. \tag{31}$$

Once we have the parameter values, we can solve equation (31) to get the value of n_2 and then check whether (30) is satisfied. The left-hand side of equation (31) is an increasing function of n_2. Without solving (31), we can derive the following result. From equation (31), when T_2 increases, n_2 increases. Thus, when the number of farmers in region 2 increases or that in region 1 decreases, the equilibrium with all workers concentrated in region 1 is less likely to be stable.

6. Conclusion

Empirical research has shown that firms located in areas with larger populations are on average larger and more productive. In this paper, we have shown that allowing firms to choose their technologies helps explaining this empirical observation. This incorporation of technology choice into a general equilibrium model of economic geography is tractable. We have established the following results analytically. First, regardless of the existence of regional trade or not, an intermediate good producer in the region with a higher number of workers produces a higher level

of output and has a lower marginal cost of production. If a worker moves from the region with a lower number of workers to the region with a higher number of workers, interestingly intermediate good producers in both regions choose less advanced technologies. Second, with regional trade, the wage ratio between the two regions is a constant and is affected by the level of transportation costs. Finally, the equilibrium that all workers concentrate in region 1 is less likely to be stable when the endowment of farmers in region 2 is relatively large.

There are some potential generalizations and extensions of the model. First, in this model we have used special functional forms in specifying fixed and marginal costs. It will be interesting to study more general cost functions. While this kind of extension may be less tractable, we believe that the main result that firms in a region with a higher number of workers will have a higher level of output and choose more advanced technologies will be robust because our main result is based on the tradeoff between marginal and fixed costs rather than on specific functional forms. Second, the model can be extended to address the dynamics of worker mobility by specifying worker mobility as a function of utility difference between the two regions. Third, as suggested by an anonymous reviewer, the model can be generalized to incorporate capital as an additional factor of production. When a worker moves from region 2 to region 1, this changes the supply of labor and affects the relative price of capital to labor and thus an intermediate firm's technology choice. Finally, in this model, intermediate good producers have market power in the goods market. It will be interesting to study government policies such as tax policies trying to address distortions from the existence of market power.

Acknowledgements

Appendix

Proof of Proposition 1:

First, equation (9) comes from equation (8). Second, from equations (1a), (1b), and (2), $f_1 + \beta_1 x_1 = \frac{\theta+\gamma}{\theta} n_1{}^\gamma$. Plugging $f_1 + \beta_1 x_1 = \frac{\theta+\gamma}{\theta} n_1{}^\gamma$ into equation (5) yields $w_1 = \frac{\gamma}{\theta+\gamma} p_1 n_1{}^\theta$. Plugging $f_1 + \beta_1 x_1 = \frac{\theta+\gamma}{\theta} n_1{}^\gamma$ into equation (6) yields $m_1 = \frac{\theta L_1}{\theta+\gamma} n_1{}^{-\gamma}$. Plugging $w_1 = \frac{\gamma}{\theta+\gamma} p_1 n_1{}^\theta$

and $m_1 = \frac{\theta L_1}{\theta+\gamma} n_1^{-\gamma}$ into equation (4) yields (11). Combining equation (11) and $m_1 = \frac{\theta L_1}{\theta+\gamma} n_1^{-\gamma}$ yields equation (10), and combining equations (2) and (11) yields (12). Plugging the value of w_1 from equation (9), the value of m_1 from equation (10), and the value of x_1 from equation (12) into (7) yields (13). ∎

Proof of Proposition 2:

From the specification of the utility function and equations (9) and (13), a worker's utility is

$$U = \frac{w}{(p_1)^{1-\alpha}} = \frac{[(1-\alpha)T_1]^\alpha}{\alpha^\alpha} \left[\frac{\gamma \delta^{\frac{\gamma}{\delta}} \theta^{\frac{2\theta}{\gamma}}}{(\theta+\gamma)^{\frac{\gamma+2\theta}{\gamma}}} \right]^{1-\alpha} L_1^{\frac{(\gamma+\theta)(1-\alpha)}{\gamma}-1}.$$

Differentiation of the above equation yields

$$\frac{dU}{dL_1} = \left(\frac{(\gamma+\theta)(1-\alpha)}{\gamma} - 1 \right) \frac{[(1-\alpha)T_1]^\alpha}{\alpha^\alpha} \left[\frac{\gamma \delta^{\frac{\gamma}{\delta}} \theta^{\frac{2\theta}{\gamma}}}{(\theta+\gamma)^{\frac{\gamma+2\theta}{\gamma}}} \right]^{1-\alpha} L_1^{\frac{(\gamma+\theta)(1-\alpha)}{\gamma}-2}.$$

Thus $\frac{dU}{dL_1} < 0$ if and only if $\theta - \gamma\alpha - \alpha\theta < 0$. ∎

Proof of Proposition 3:

From equation (5), the level of output for an intermediate good producer in region 1 is

$$x_1 = \frac{f_1 w_1}{p_1 - \beta_1 w_1}. \tag{A1}$$

Combining equations (16) and (19) yields

$$m_1 x_1 + (1+t) m_2 x_2 = \frac{(1-\alpha)}{\alpha p_1} (T_1 + T_2). \tag{A2}$$

Plugging (A1) and (A2) into equation (20) yields

$$\left(\frac{p_1}{p_1 - \beta_1 w_1} \right)^2 \alpha f_1 w_1 - (1-\alpha)(T_1 + T_2) = 0. \tag{A3}$$

Combining equations (1a), (1b), (2) with (A1) yields $n_1 = \left[\frac{(\theta+\gamma)w_1}{\gamma p_1} \right]^{\frac{1}{\theta}}$. Plugging this result into (A3) yields

$$w_1 = \left[\frac{\delta(1-\alpha)(T_1+T_2)\theta^2 \gamma^{\frac{\gamma}{\theta}}}{\alpha(\theta+\gamma)^{2+\frac{\gamma}{\theta}}} p_1^{\frac{\gamma}{\theta}} \right]^{\frac{\theta}{\gamma+\theta}}. \tag{A4}$$

From equation (5*), the level of output for an intermediate good producer in region 2 is

$$x_2 = \frac{f_2 w_2}{p_2 - \beta_2 w_2}. \tag{A5}$$

Plugging (A2) and (A5) into (20*) yields

$$\left(\frac{(1+t)p_1}{(1+t)p_1 - \beta_2 w_2}\right)^2 \alpha f_2 w_2 - \delta(1-\alpha)(T_1 + T_2) = 0. \tag{A6}$$

Combining equation (1a), (1b), (2*), and (A5) yields $n_2 = \left[\frac{(\theta+\gamma)w_2}{\gamma(1+t)p_1}\right]^{\frac{1}{\theta}}$. Plugging this result into (A6) yields

$$w_2 = \left[\frac{\delta(1-\alpha)(T_1+T_2)\theta^2 \gamma^{\frac{\gamma}{\theta}}(1+t)^{\frac{\gamma}{\theta}}}{\alpha(\theta+\gamma)^{2+\frac{\gamma}{\theta}}} p_1^{\frac{\gamma}{\theta}}\right]^{\frac{\theta}{\gamma+\theta}}. \tag{A7}$$

Equilibrium values of variables are derived as follows. First, plugging the value of w_1 from equation (A4) and the value of w_2 from equation (A7) into (16) yields (21). Second, plugging the value of p_1 from equation (21) into (A4) yields (22). Similarly, plugging the value of p_1 from equation (21) into (A7) yields (23). Third, plugging the value of p_1 from equation (21) and the value of w_1 from equation (22) into $n_1 = \left[\frac{(\theta+\gamma)w_1}{\gamma p_1}\right]^{\frac{1}{\theta}}$ yields (24). Similarly, plugging the value of p_1 from equation (21) and the value of w_2 from equation (23) into $n_2 = \left[\frac{(\theta+\gamma)w_2}{\gamma(1+t)p_1}\right]^{\frac{1}{\theta}}$ yields (25). Fourth, plugging the value of n_1 from equation (24), the value of w_1 from equation (22), and the value of p_1 from equation (21) into (A1) yields (26). Similarly, plugging the value of n_2 from equation (25), the value of w_2 from equation (23), and the value of p_1 from equation (21) into (A5) yields (27). Finally, plugging the value of n_1 from equation (24) and the value of x_1 from equation (26) into (6) yields (28). Similarly, plugging the value of n_2 from equation (25) and the value of x_2 from equation (27) into (6*) yields (29). ∎

Proof of Proposition 4:

Plugging $L_2 = L - L_1$ into equations (24) and (25) yields

$$n_1 = \delta^{\frac{1}{\gamma}}\left(\frac{\theta}{\theta+\gamma}\right)^{\frac{2}{\gamma}}\left[\left(1 - (1+t)^{\frac{\gamma}{\gamma+\theta}}\right)L_1 + (1+t)^{\frac{\gamma}{\gamma+\theta}}L\right]^{\frac{1}{\gamma}},$$

$$n_2 = \delta^{\frac{1}{\gamma}}\left(\frac{\theta}{\theta+\gamma}\right)^{\frac{2}{\gamma}}\left[\left(1 - (1+t)^{\frac{\gamma}{\gamma+\theta}}\right)L_1 + (1+t)^{\frac{\gamma}{\gamma+\theta}}L\right]^{\frac{1}{\gamma}}/(1+t)^{\frac{1}{\gamma+\theta}}.$$

Since $1 - (1+t)^{\frac{\gamma}{\gamma+\theta}} < 0$, differentiation of the above two equations yields that $\frac{dn_1}{dL_1} < 0$

and $\frac{dn_2}{dL_1} < 0$. ∎

Proof of Proposition 5:

When all workers are concentrated in region 1, the following equilibrium conditions are valid:

$$f'(n_1) + \beta'(n_1)x_1 = 0, \tag{2}$$

$$p_1 x_1 - (f_1 + \beta_1 x_1)w_1 = 0, \tag{5}$$

$$\alpha w_1 L - (1-\alpha)(T_1 + T_2) = 0, \tag{A8}$$

$$\left(\frac{p_1}{p_1 - \beta_1 w_1}\right)^2 \alpha f_1 w_1 - \delta(1-\alpha)(T_1 + T_2) = 0. \tag{A9}$$

Equation (A8) is the condition for the clearance of the market for the agricultural good in region 1. Equation (A9) comes from an intermediate good producer's optimal choice of output. Solving the set of equations (2), (5), (A8), and (A9) yields

$$w_1 = \frac{(1-\alpha)(T_1 + T_2)}{\alpha L}, \tag{A10}$$

$$p_1 = \frac{(1-\alpha)(T_1 + T_2)(\theta + \gamma)^{\frac{2\theta+\gamma}{\gamma}}}{\alpha \gamma^{\frac{\theta}{\gamma\theta}} \gamma^{\frac{2\theta}{\gamma}} L^{\frac{\gamma+\theta}{\gamma}}}. \tag{A11}$$

For a worker moving to region 2 and maintaining the same level of utility as a worker in region 1, from the specification of a consumer's utility function and equation (15), the lowest wage rate in region 2 should satisfy

$$w_2 = w_1(1+t)^{1-\alpha}. \tag{A12}$$

For an intermediate good producer moving to region 2, its profit is $(1+t)p_1 x_2 - (f_2 + \beta_2 x_2)w_2$. For this firm to make a nonnegative profit, we need

$$(1+t)p_1 x_2 - (f_2 + \beta_2 x_2)w_2 \geq 0. \tag{A13}$$

Total income in region 2 is the sum of income from farmers T_2 and workers in this region $(f_2 + \beta_2 x_2)w_2$. Thus, total income in region 2 is $T_2 + (f_2 + \beta_2 x_2)w_2$. Since $1 - \alpha$ percent of income is spent on the manufactured good, demand for the firm moving to region 2 is $(1-\alpha)[T_2 + (f_2 + \beta_2 x_2)w_2]$. This firm's revenue is $p_2 x_2$. Thus, we have $(1-\alpha)[T_2 + (f_2 + \beta_2 x_2)w_2] = p_2 x_2$. Rearrangement of this equation yields

$$x_2 = \frac{(1-\alpha)(f_2 w_2 + T_2)}{(1+t)p_1 - (1-\alpha)\beta_2 w_2}. \tag{A14}$$

This intermediate good producer chooses its technology to maximize profit $(1+t)p_1 x_2 - (f_2 + \beta_2 x_2)w_2$. The first order condition with respect to n_2 is $[(1+t)p_1 - \beta_2 w_2]\frac{\partial x_2}{\partial n_2} - (f_2' + \beta_2' x_2)w_2 = 0$. It can be checked that $[(1+t)p_1 - \beta_2 w_2]\frac{\partial x_2}{\partial n_2} = 0$. The intuition behind this is that the level of technology is optimally chosen for a given level of output. Thus, this intermediate good producer's optimal choice of technology degenerates to $-(f_2' + \beta_2' x_2)w_2 = 0$. Rearrangement of this equation yields

$$x_2 = -\frac{f_2'}{\beta_2'}. \tag{A15}$$

Equations (A14) and (A15) lead to

$$-\frac{f_2'}{\beta_2'} = \frac{(1-\alpha)(f_2 w_2 + T_2)}{(1+t)p_1 - (1-\alpha)\beta_2 w_2}.$$

Using the specifications of fixed and marginal costs, the above equation yields equation (31) defining n_2.

For (A13) to be invalid, from equations (1a), (1b), (A12), and (A15), the following is needed:

$$(1+t)\gamma p_1 n_2^{\gamma+\theta} - (\gamma + \theta)w_2 n_2^{\gamma} < 0. \tag{A16}$$

Plugging the value of w_1 from (A10) and p_1 from (A11) into (A16) yields

$$n_2 < \frac{\alpha^{\frac{1}{\theta}} L^{\frac{\theta+\gamma}{\gamma\theta}} \delta^{\frac{1}{\gamma}} \theta^{\frac{2}{\gamma}}}{(1+t)^{\frac{\alpha}{\theta}}(\theta+\gamma)^{\frac{2}{\gamma}}}. \blacksquare$$

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