Why Is It Difficult to Adopt Innovative Technologies? The Role of Coordination and Collateral Borrowing in Technology Adoption

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Adopting highly innovative technologies is difficult due to many socioeconomic factors. We analyze the economic mechanisms associated with the large fixed costs jointly faced by various subsectors of an economy and the financing difficulty. We construct a Romer (1990) type growth model of technology adoption with fixed cost and then analyze macro dynamics showing why adopting innovative technology is difficult. We show that exercising coordination power in centralized economies can boost aggregate demand, facilitating the adoption of new technologies. Similarly, collateral lending in decentralized economies can play the role of helping technology adoption. Only when a threshold level of investment (i.e., the tipping point) is funded will the increasing returns to scale property arising from fixed costs generate a dynamic path toward a stable equilibrium with high output. We draw some implications.

Keywords: technological changes, coordination, big push, collateral lending

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I. Introduction

Despite the obvious benefits of adopting new technology, only a few countries are successfully adopting it. Technology leaders in the current world economy enjoy the benefits of fast economic growth, low poverty, and persistent innovation possibilities given the "learning by doing" in technology development. Many factors including culture, institutional quality, legal system, social capital, the degree of protecting property rights, the abundance of skilled labor, and aversion to new technology, among others, obviously affect the ability of a country to adopt new technologies. Apart from the usual factors as mentioned above, this paper attempts to focus on examining some fundamental economic mechanisms which cause a delay in technology adoption.

Interestingly, not only advanced decentralized economies but centralized economies become technology leaders in recent decades. Countries such as the U.S. which has advanced financial markets with strong property rights protection usually become technology leaders. Centralized economies such as China and the former Soviet Union are also surprisingly well known to conduct or have conducted technological innovations at least for certain periods of time.

Technological change is the essential basis of modern economic growth (*e.g.*, Romer, 1990). The apparently simple relationship between technological change and economic growth/asset price, to name a few, is actually more complex than we casually think given that (i) adopting new innovative technologies requires a large-scale simultaneous initial investment across sectors (*e.g.*, ICT network infrastructures) for their general purpose nature, and (ii) the infrastructure investment needs proper financing. In fact, financing is not easy for individual firms and sectors because adopting innovative technology in a small subset of sectors would not sufficiently increase aggregate income, such that firms will face insufficient aggregate demand and low profitability, eventually leading to failure in the investment for technology adoption. In the context of big push theory (*e.g.*, Murphy *et al.*, 1989), this point can be taken as a coordination failure problem.[1]

[1] An example of the coordination problem is the case where many different sectors are potential demanders of a new technology. Subsidizing a sector alone that develops the new technology does not guarantee the adoption because firms in other sectors face very weak adoption incentives. This case is especially true

This paper examines the fundamental question why adopting new technologies is difficult despite the obvious potential gains from adopting them. We attempt to highlight the insight that new innovative technologies involve not only a handful of subsectors but nearly all subsectors in an economy to jointly make a large fixed infrastructure investment, which is prohibitively costly. Technology adoption arises when such fixed costs require financing across all different sectors given the general purpose nature of influential breakthrough technologies. If only a few sectors invest but the rest do not, the new innovative technology cannot take root in an economy. Therefore, financing the large fixed costs is essential in adopting new technologies. Naturally, the notion of coordination across subsectors is important, not to mention the large investment resources, which are usually difficult to obtain.

Centralized economies with coordination power can successfully handle the thorny coordination issues by exercising discretionary power and mobilizing investment resources for technology adoption. Accordingly, they often become technology leaders in the modern decades. Decentralized economies with highly developed financial markets can also suffer from coordination problem due to a lack of investment fund. Determining "angels" financing investment is difficult in anticipation of future success. In this case, collateral borrowing can be a useful method to provide additional investment sources for technology adoption.

We construct a Romer (1990) type growth model of technology adoption with fixed cost. Then, by incorporating coordination power and/or collateral lending into a simple growth model, we show that coordination power in centralized economies and/or collateral lending in decentralized ones can boost aggregate demand, facilitating the adoption of new technologies. Once a threshold level of investment is funded, the increasing returns to scale property arising from fixed costs generates a dynamic path toward a stable equilibrium with high output.

This paper provides some policy implications. First, market failing features and/or missing markets exist in adopting innovative technologies. Private markets may not perfectly handle technology adoption for coordination issues and a lack of resources given the large

when adopting a new technology that involves discarding old technologies, so that the fixed cost is large.

fixed costs. Second, proper policy interventions at the government level can often be justified, such as by providing proper coordination services. Third, collateral borrowing in the period of new innovative technology development might be warranted for social welfare.

The essential elements of this paper are in line with the following past literature. Big push theory (*e.g.*, Murphy *et al.*, 1989) typically addresses the coordination failure problem. We highlight the particular nature of a coordination failure problem in innovative technology adoption and discuss proper external coordination mechanisms (*e.g.*, government intervention in subsectors) which might be necessary for adopting efficient new big technologies, unless the financial markets are extremely developed.

Meanwhile, several theoretical studies are related to ours, analyzing the relationship between collateral value, investment, and economic growth. Without a formal model, Morck (2021) also notes that innovation is chronically underfunded because positive spillovers give investment in innovation a social rate of return several times higher than its internal rate of return to innovators. He writes that seemingly irrational exuberance (*e.g.*, manias) compensates for chronic underinvestment in innovation, and innovation-related bubbles have a positive role. In our context, asset price increases based on collateral borrowing may help adopt new technologies in the presence of large fixed costs that need simultaneous financing across sectors.

With the proposed notion of credit market frictions, Kiyotaki and Moore (1997) highlight the importance of collateral value as an investment source. They demonstrate the cumulative effects of collateral value on investment: a decrease in investment lowers future revenues, leading to a drop in collateral value. In turn, this scenario further decreases investment.[2] Apart from this cyclical property of collateral, we

[2] In a related context, Kashyap *et al.* (1993) present a model that produces multiple equilibria in which expectations of high growth of future output leading to high land prices are self-fulfilling. In a similar context, Kim and Lee (2002, 2006) construct a model of self-fulfilling multiple equilibria: Investors' optimistic expectations on the future economy increases collateral value, resulting in higher investment and thus higher economic growth. Even a more positive view to bubbles can be found where busted bubbles in fact imply an oversupply of capital, which will be used later at a cheaper user cost of capital for expanding production capacity in the future boom (*e.g.*, Cochrane, 2002; McGrattan and Prescott, 2001; 2003; 2005; 2006).

take advantage of the feature that collateral lending or borrowing can provide an additional source of investment for technology adoption in the growth context.

Drawing on Romer's (1990) variety expansion model, we build an endogenous growth model with technology adoption under a substantial fixed cost of investment, where the new technology requires a fixed cost in production, a source of increasing returns to scale in investment funds. Collateral lending can facilitate technology adoption as follows. Anticipating that firms will adopt the new technology can raise the asset price. With this anticipation, agents can consume and save/invest more owing to additional borrowing from the asset price increase.[3] This situation defines an equilibrium of new technology adoption with collateral borrowing. Conversely, a lack of proper coordination and investment funds leads to the expectation that firms cannot adopt the new technology, blocking the mechanism for technology adoption. Aghion *et al.* (2005) also present the role of credit constraint in the Schumpeterian growth model. By contrast, our standard growth model focuses on the fixed cost required for big technology adoption and the implications of credit constraint along with equilibrium multiplicity. Our results are broadly consistent with the empirical finding of Bircan and De Hass (2019) showing that technology adoption is more frequent in firms facing less financial constraint.

The paper proceeds as follows. Section II describes the basic model of technology adoption without external investment resources, i.e., self-financing only. Section III presents the model where external investment resources are available through (i) centralized coordination power in planned economies or (ii) collateral borrowing in decentralized economies based on the asset value. We characterize equilibrium for each case using simple, intuitive graphs, leaving technical proofs to appendices and then discuss the model's implications. Section IV

[3] As can be seen later in further detail, this scenario happens when the growth rate exceeds the interest rate, which is a typical situation in an economy with an over-supply of credit or with an industrial policy-driven low interest rate for economic development. Interestingly, this condition is satisfied in the US. As the supplier of the world reserve currency dollar, the US borrows money from the rest of the world by selling TB at the rate much lower than the yield rate from the US investment in developing countries. The gap between these two rates can be explained by reserve currency premium apart from the risk premium.

concludes the paper.

II. Basic Model

We build a simple growth model where the resources for investment come from national savings only, and a market (*i.e.*, no angel) is missing for providing financial services to finance large fixed costs for future economic growth, i.e., coordination failure. To this end, we extend Romer's (1990) variety expansion model by incorporating the fixed cost of initial investment. We begin with describing the environment where investment for new technology adoption should be financed by savings without other financing mechanisms. Then, we move on to the case where government coordination power and/or collateral borrowing help provide further credit, *i.e.*, an additional source of investment in Section III.

A. Environment

We consider the situation where big technologies now arrived exogenously. Agents are aware of their arrival and take them as a rare event that virtually lasts once and for all in their time frame. Given that new technology permanently raises output, adopting new innovative technologies has obvious potential gains. The adoption of big technological changes requires new simultaneous investment across different industries/sectors. Some technologies are often not adopted because of the following two reasons. First, breakthrough technologies require large fixed investment costs, with difficulty in financing for scarce resources for investment. Second, even if funds are sufficient, the following coordination problem persists: not only the sufficient investment of one sector but adequate investment of other sectors should occur simultaneously to ensure the successful adoption of general-purpose big technologies across the economy. Later, we will specify the nature of new breakthrough technology by embedding the variety of intermediate goods production to the model as a basis of technology. We will also examine under what conditions technology adoption actually occurs.

Knowing the technologies and their adoption/non-adoption based on the availability of income sources and difficulties in successful simultaneous financing across industries, agents determine consumption and savings, which will be used for financing the investment in intermediate goods industries for adopting new technologies. Endogenous growth happens temporarily when a new technology is adopted and until the economy converges to a long-run steady state. We first show the equilibrium and dynamics under a given technology and later consider technology adoption decisions.

A) Firms

The final output is produced in the competitive market, following Romer's variety expansion production technology:

$$Q_t = [\int_0^m x_t(j)^{\frac{\theta-1}{\theta}} dj]^{\frac{\theta}{\theta-1}}, \tag{1}$$

where Q_t represents the amount of the final output at time t, m is the number of intermediate goods that serves as a measure of technology (a greater m means more advanced technology), $x_t(j)$ is that of the j-th intermediate good at time t, and θ is the elasticity of substitution among intermediate goods with $\theta > 1$ as assumed in the related literature. This form of Q_t given in (1) shows that the variety of technologies m raises production, holding other things constant. The production function exhibits a constant returns to scale (CRS) property.

The intermediate goods are produced in monopolistically competitive markets using the following technology:

$$x_t(j) = (A_t Z)^{1-\alpha} \cdot [k_t(j) - f_m(j)]^{\alpha}, \tag{2}$$

where α is the share for capital with $0 < \alpha < 1$; $k_t(j)$ is the investment for the j-th intermediate good production at time t; and $f_m(j)$ is an arbitrarily large fixed cost required for the production of intermediate good (sector) j under technology m, which should be financed; $A_t = (1+g)^t A$ represents the productivity of firms producing intermediate goods, increasing with a constant growth rate g; z is the externally given fixed input (*e.g.*, land, skilled labor force), normalized at unity. For analytical convenience, we pose the following assumptions: (i) f_m is viewed as the annuitized flow value corresponding to the total fixed cost associated with innovative technology adoption. The flow value version of the fixed cost allows us to deal with the fixed cost in the balanced growth path;[4] (ii) it rises with m, implying that new advanced technology involves a greater level of initial investment: $f_{m'} > f_m$ for $m' > m$; (iii) its growth rate is also set at g; thus, we can handle a balanced growth equilibrium with a fixed cost.

In the long-term steady state, a constant returns-to-scale property holds given that A_t, k_t, and f_m grow at the same rate; however, in the short-term equilibrium, profits can arise due to the decreasing returns to scale (DRS) feature of (2) at a given f_m.[5] The profits are distributed to individuals in the form of dividends. A more thorough description of the profit maximization problem for intermediate good producers is in Appendix C. We do not endogenize the R&D sector, treating them as exogenous for simplicity. Therefore, given the external development process of new technologies, intermediate good firms, including new and existing intermediate goods firms, should forgo the fixed cost f_m when adopting technology m. In what follows, we detrend all growing endogenous variables including final output, intermediate goods, and their investment using the constant growth trend with a growth rate of g, except when we need to discuss in nominal terms. As seen later, the fixed cost is essential in our model because it can generate non-convexity in the production set, a source of self-fulfilling multiple equilibria. To simplify the problem without loss of generality, we further assume that capital depreciates 100% in a period as in Long and Plosser (1983).[6] We may assume that the unit of a period in this paper

[4] To precisely express a one-time fixed cost into a flow value counterpart, agents are assumed to know how long a new big technological change lasts after its adoption. Alternatively, given that it takes a while for another new technology to arrive and become commercialized, we may see that as $r \cdot$ fixed cost where r is the external low borrowing cost per period.

[5] As shown later, this DRS feature technically ensures a stable long-run equilibrium for concavity. It is also based on the view that invention is a difficult, creative process and depends crucially on the size of fixed input and/or the ability of skilled workers Z who produce intermediate goods with knowledge of existing inventions and whose number does not grow in proportion to the level of investment (or is fixed). Technically, we can see this as $x_t(j) = (k_t(j) - f_m)^{\alpha}(A_t Z)^{1-\alpha} = A_t^{1-\alpha}(k_t(j) - f_m)^{\alpha}$, where Z is normalized at unity. α is usually taken as around 1/3, but if capital includes human capital, it can be around 2/3 according to Mankiw Romer and Weil [1992].

[6] This assumption is used for analytical tractability. Long and Plosser (1983) made a set of assumptions such as discrete timing interval, log utility, Cobb-Douglas technology, and a 100 percent depreciation of capital. For further

is sufficiently long.

The production function *per se* exhibits a constant returns-to-scale (CRS) property with respect to x_t. The equilibrium output that uses symmetric intermediate goods under technology m is expressed as a function of capital and fixed cost:

$$Q_t = [\int_0^m x_t(j)^{\frac{\theta-1}{\theta}} dj]^{\frac{\theta}{\theta-1}} = m^{\frac{\theta}{\theta-1}} x_t(j) = m^{\frac{\theta}{\theta-1}} A_t^{1-\alpha}(k_t - f_m)^{\alpha}. \quad (3)$$

The production function retains an increasing returns to scale (IRS) property with respect to k_t at least up to a certain level of capital as shown in Figure 1: note that the slope of the line connecting the origin and a point on the production function rises with capital. This phenomenon is exclusively due to the presence of fixed costs associated with new technology adoption: without the fixed cost, a decreasing returns to scale feature will dominate. Therefore, investing more will lower average cost, leaving additional profits to firms.

B) Financial sector

As in the recent macroeconomics literature, we also allow for frictions in the financial market. The financial intermediation between individual investors and intermediate goods-producing firms with potential future profits is difficult for asymmetric information. Therefore, borrowing is usually difficult. Accordingly, this section assumes that investment should be internally financed, unless external resources are available. If any, borrowing can happen on the basis of government coordination power and/or collateral as in Kiyotaki and Moore (1997) as will be shown later. Firms may not receive adequate investment funds, creating a coordination problem for adopting big technologies.

At this point, we assume that highly advanced financial markets help coordinate given investment resources across firms in industries on the arrival of technological changes, using a set of abundant pieces of information. However, they cannot overcome a lack of investment resources, given the difficulty of finding "angels" financing investment in anticipation of future success. By contrast, economies with less developed financial markets suffer from the coordination problem

discussion on this topic, refer to Smith (2006).

as mentioned above. Other than a lack of sufficient investment fund, properly distributing scarce resources across sectors may be challenging. This study assumes that centrally planned economies with less developed financial system retain the coordination authority to distribute scarce resources across sectors properly. Therefore, the remaining issue with the coordination problem in financing breakthrough technologies is the magnitude of investment funds in the financial markets or an equivalent system in planned economies. This section now deals with this type of coordination problem when investment is financed through savings only. Some studies argue that the behavioral specificities of the stock markets (*e.g.*, psychology, mania, optimism and pessimism, etc.) are crucial for adopting big technologies. We also take them as potentially important but begin with focusing on rationality in the assessment of new technologies. Later, we will discuss the role of behavioral factors.

For analytical tractability, we make a standard assumption that the representative agent owns the firms producing final output and also invests in a fund. The fund invested in the market portfolio consists of the equities of firms producing intermediate goods and in each period distributes all returns from this market portfolio investment to the representative agent due to competition.[7] Thus, the yield rate of the fund r_t^m will be determined at the end of each period.

Then, the following can be easily inferred: with the logarithmic utility, the agent consumes a $1-\beta$ fraction of the current income/wealth, and the rest of the wealth will be saved and invested in a steady state.[8] Presenting formal optimization of the model and the specific features of

[7] Advanced financial markets help in coordinating the allocation of investment funds across individual intermediate good producers, especially when investment source is scanty. However, as seen later, an abundant inflow of investment fund from individuals through collateral borrowing based on expectation of a future housing asset value rise can help resolve the coordination problem in general.

[8] As we see from individuals' problem, output is distributed to representative agents in the form of the returns to savings including firm's profits. In addition, we are assuming that all firms are owned by one investment fund to simplify the problem. This assumption ensures coordination among various intermediate good producing firms when adopting new technologies because without proper coordination, new technologies incurring a huge amount of fixed cost would not be adopted although they can make possible high returns to investors of the fund.

the general equilibrium is part of the paper's contribution. For brevity, a detailed discussion can be found in Appendix C. Here, we characterize only equilibrium and some notable features of our model.

C) Individuals

The representative agent's preferences are described by:

$$\max_{\{c_t, s_t, Q_{t+1}\}} \sum_{t=0}^{\infty} \beta^t [\log(c_t) + \varphi \log(h_{t-1})],$$
$$\begin{aligned} s.t.\ (i)\quad & c_t + s_t = Y_t \\ (ii)\quad & Y_{t+1} = (1 + r_t^m) s_t \\ (iii)\quad & Y_t = Q_t \\ (iv)\quad & h_t = \bar{h} \textit{ for all t's: fixed supply} \end{aligned} \tag{4}$$

where β represents the time discount rate; c_t is the consumption for period t; h_{t-1} is housing size determined at the end of the previous period $t - 1$ (or at the beginning of t) from which housing service is derived for period t; φ is the weight on the utility derived from the housing service relative to consumption; s_t is the saving to be used for funding the intermediate goods production through funds; and Y_t is the income of the representative agent, which is equal to output Q_t. The budget constraint (i) simply states that income is spent on consumption and saving. Constraint (ii) shows that savings are invested to yield returns on intermediate goods investment, $(1+r_t^m)s_t$; moreover, possible profits in the intermediate goods sector will be distributed to individuals through fund returns r_t^m for period t, which become the source of income in the next period Y_{t+1}. Constraint (iv) of $h_t = \bar{h}$ simply states that the exogenously given quantity of housing yields a fixed supply of housing service. Although we do not optimize on housing h_t, we can still determine the shadow value of housing as it raises utility through preferences on housing. When consumer financing becomes available, collateral lending is based on the housing asset as can be seen later. Notably, we are assuming that all firms are owned by one investment fund to simplify the problem. A straightforward optimization process reveals the Euler equations for all t:

$$\frac{1}{c_t} = \beta(1 + r_t^m) \frac{1}{c_{t+1}}, \tag{5}$$

$$Q_{t+1} = (1 + r_t^m)s_t. \tag{6}$$

Manipulating these two equations yields the equations for consumption and saving:

$$c_t = (1 - \beta)Q_t \tag{7}$$

$$s_t = \beta Q_t. \tag{8}$$

Given the log utility, a constant fraction β of income is saved, and the rest is consumed.[9]

Presenting formal optimization of the model and the specific features of the general equilibrium is part of the paper's contribution. A detailed discussion can be seen in Appendix C. Here, we only characterize equilibrium and some notable features of our model.

D) Describing equilibrium

As in the Romer model, we assume the existence of many identical workers and firms of a unit measure, respectively. We also posit that the final goods market is competitive, while the intermediate goods markets are monopolistically competitive. We first describe the equilibrium without collateral borrowing. The derivation of the equilibrium of the model partly depends on the standard routine of the Romer model. Owing to simplifying assumptions, the main results of the paper rely crucially on the two equations: (i) an equation describing the nature of output production with capital investment as input; and (ii) a general equilibrium equation that saving equals investment, where saving is a constant fraction of income, a useful feature that the logarithmic utility function delivers. Intermediate good producing firms will adopt new technology if the latter raises profits and if investment funding is available through the financial market or government's coordination.[10]

[9] Using $Q_{t+1} = \left(1 + r_t^m\right)(Q_{t+1} - s_t)$, we can derive the condition. $c_t + \frac{c_{t+1}}{\left(1 + r_t^m\right)} + \frac{c_{t+2}}{\left(1 + r_t^m\right)\left(1 + r_{t+1}^m\right)} + \ldots = Q_t$. Then, using (6), we can confirm the proportional allocation of output to consumption and saving.

[10] We assume here that profits should be non-negative. For brevity, we exclude the technical condition in the text.

E) Pricing the housing value

To simplify the problem, we assume that the economy has been at a steady state relying on the old technology described by the steady state final output and investment in each intermediate good, $\{Q(m)^*, K(m)^*\}$. Using the specific form of the preferences, $U(t) = \log(c_t) + \varphi\log(h_{t-1})$ and standard asset pricing models under rational expectations, we can express the housing price using the shadow value of a house. Defining housing price as the product of a unit price *qt* and $\bar{h}$ units at time *t*, the present value of housing service flows from the representative agent's problem given by (4) is as follows:

$$\begin{aligned} h \cdot q_t &= h \cdot \frac{1}{u'(c_t)}[\varphi\omega'(h) + \beta\varphi\omega'(h) + \beta^2\varphi\omega'(h) + \ldots] \;\; (present \;\; value) \\ &= \varphi c_t(1 + \beta + \beta^2 + \ldots) \quad (\because \log \;\; utility \quad used) \\ &= \varphi c_t \cdot \frac{1}{1-\beta} \\ &= \varphi \cdot Q_t \quad (\because c_t = 1-\beta)Q_t \; used), \end{aligned} \tag{9}$$

where the second line is based on the functional assumption, $\omega(H) = \varphi\log(H)$. Equation (9) shows that under a logarithmic utility, housing price is expressed as a certain fraction of output.[11]

B. Dynamics

With these model features, we can characterize the dynamics of final output and the investment for an intermediate good under a given technology *m*. Given the purposely simplified setting, we can describe the model's dynamics using the following two equations:

Dynamics 1: No borrowing case (see Figure 1)

$$Q_t = m^{\frac{\theta}{\theta-1}} A_t^{1-\alpha}(k_t - f_m)^\alpha \;\; or \;\; Q_t = m^{(\frac{\theta}{\theta-1}-\alpha)} A_t^{1-\alpha}(K_t - mf_m)^\alpha, \tag{10}$$

[11] Notably, the interest rate does not appear in (9) because both income and substitution effects of a change in the interest rate, expected or unexpected, completely cancel each other out, so that the housing demand is independent of the level of the interest rate.

$$k_t = \frac{\beta}{m} Q_{t-1} \ \ or \ \ K_t = \beta Q_{t-1}, \tag{11}$$

where the symmetries of $x_t = x_t(j)$, $k_t = k_t(j)$ and $f_m = f_m(j)$ have been used for all $j \in [0, m]$ for simplicity as in the related literature. To derive Equation (10), the aggregate production function for the final output, we use the symmetry of $k_t = k_t(j)$. The fixed cost f_m makes production function non-convex (see Figure 1). Moreover, Equation (11) is derived from the general equilibrium condition that total investment $m \cdot k_t$ equals total saving (a β fraction of the previous period's income Q_{t-1}), utilizing the symmetry of $k_t = k_t(j)$.

Equations (10) and (11) can be transformed to the detrended counterparts by detrending the output and capital variables by the growth rate as follows:

$$\tilde{Q} = m^{(\frac{\theta}{\theta-1}-\alpha)} \tilde{A}_t^{1-\alpha} (\tilde{K}_t - m\tilde{f}_m)^{\alpha}, \tag{12}$$

$$\tilde{K}_t = \frac{\beta}{1+g} \tilde{Q}_{t-1}, \tag{13}$$

where the variables with tildes (~) on top in Equations (12) and (13) represent those detrended by the growth rate g_t: $\tilde{x}_t \equiv x_t / \prod_{i=1}^{t}(1+g_i)$, where $g_i = g$ in steady states, and $\tilde{A}_t$ is detrended similarly: $\tilde{A}_t = A$.

The dynamics of income and investment for each firm producing an intermediate good over time is described in Figure 1 where final output and investment are denoted by the detrended notations: $\tilde{x}_t \equiv x_t / \prod_{i=1}^{t}(1+g_i)$. In Figure 1, the point $\{\tilde{Q}(m)^*, \tilde{K}(m)^*\}$ represents a pair of the "stable" steady state levels of final output and investment of each intermediate good defined under the use of the existing, old technology. Furthermore, the point $\{\tilde{Q}(m)_*, \tilde{K}(m)_*\}$ represents a pair of the "unstable" steady state values under the old technology. Figure 1 also shows that the stable steady state is unique. The following proposition describes the technical conditions required for the existence of two solutions.

Proposition 1: Conditions for multiple equilibria.

Suppose that the fixed cost in production is given by $f_m(t) = c \cdot m^{\mu} = \tilde{c}(1+g)^t m^{\mu}$, where c grows at the rate of g. Both $(\theta + \frac{\alpha}{\alpha-1})(\frac{1}{\theta-1}) > 1 + \mu$

and $(\frac{\beta}{1+g})^{\frac{1}{1-\alpha}} A^{(\frac{\theta}{\theta-1}-\alpha)(\frac{1}{1-\alpha})}(\alpha^{\frac{\alpha}{1-\alpha}} - \alpha^{\frac{1}{\alpha}}) \geq \tilde{c}$ are a set of sufficient conditions for the existence of multiple equilibria, one stable and the other unstable for all m.

Proof. See the proof in Appendix A.▪

A) Condition for technology adoption

We begin with the situation where the old technology m is currently being used. Now, a new technology is available. In our model, we describe a new technology m' as the one that requires an increased number of intermediate goods, *i.e.*, $m' > m$.[12] Given that technology adoption involves a large fixed cost; once a new technology is adopted, it is used until a further new technology becomes available. We assume that upon adoption decision, new technology can be adopted immediately once the fixed cost is financed. A new technology m' involves greater output and initial fixed cost. In contrast to the point $\{\tilde{Q}(m)^{*}, \tilde{K}(m)^{*}\}$ representing the stable equilibrium with the old technology, $\{\tilde{Q}(m')^{*}, \tilde{K}(m')^{*}\}$ in Figure 2 corresponds to the innovative, new technology counterpart. We also define that point $\{\tilde{Q}(m')_{*}, \tilde{K}(m')_{*}\}$ is the unstable equilibrium under new technology. What determines technology adoption is a central topic to be discussed below.

Suppose that the steady state final output under old technology $\tilde{Q}(m)^{*}$ is higher than $\tilde{Q}(m')_{*}$. This condition implies that, with the capital stock (saving) available under the current steady state income $\tilde{Q}(m)^{*}$, the new technology is successfully financed, which yields a positive profit despite its large fixed cost, i.e., the adoption of new technology. A detailed discussion of the specific meaning for the inequality of $\tilde{Q}(m)^{*} \geq \tilde{Q}(m')_{*}$ can be found in Appendix B. Here, we present the economics behind the inequality. With new technologies adopted, the economy benefits from the level effect and a temporary growth effect during the transition to a new steady state; but no long-term growth

[12] In fact, introduction of a new technology to the production process involves employment of new intermediate goods, which includes not only physical investment but also intangible investment such as "expensed investment" and/or "sweat investment" whose existence is emphasized in McGrattan and Prescott (2003, pp. 14–15). In any case, they require non-negligible fixed costs.

effect occurs: technological innovations lead to a jump in the output level, but the growth rate remains at g in the new steady state with new technologies.

Conversely, suppose that the inequality does not hold, i.e., if $\tilde{Q}(m)^*$ is lower than $\tilde{Q}(m')_*$, the new technology is not successfully financed; thus, firms do not adopt the new technology despite the fact that $\tilde{Q}(m')^* > \tilde{Q}(m)^*$, wasting the opportunity to improve social welfare. This scenario is anticipated because even if all available savings are invested in new technology adoption, intermediate good producing firms will find that (i) their profits are less than those using the current technology; additionally, (ii) their future profits worsen over time due to a dynamic leading to an economic crash. Thus, this situation discourages intermediate good producing firms from adopting the new technology.

More intuitively, we can say that the larger the gap between m' and m (the more path-breaking the new technologies), the more likely this inequality holds. That is, if the technological change is sufficiently huge, they are unlikely to make profit due to a huge fixed production cost of adopting the new technology. Thus, we have the following lemmas based on the discussion above. See Appendix B for a more technical discussion.

Lemma 1: Condition for technology adoption.

If $Q(m)^* \geq Q(m')_*$ firms adopt the new technology; if $Q(m)^* < Q(m')_*$, they do not, which we call the coordination failure.

Lemma 2: Growth effects of new technologies.

Adoption of new technologies generates the level effect and a temporary growth effect during the transition to a new steady state.

An alternative interpretation of our results is that technology adoption is difficult due to the large fixed cost. However, once the fixed cost can be covered, the economy can grow robust without vulnerability to external shocks. Before moving on to the case where borrowing is possible under the usual collateral constraint, we summarize the main conclusion from Section II using the following proposition.

Proposition 2: Robust but rare technology adoption under no borrowing.

(i) Technology adoption decision is not based on borrowing; thus, arrival of credit shocks does not affect the economy. However, (ii) technology adoption becomes difficult due to a lack of investment.

III. Extensions: allowing for further credit supply

Section III sketches some conceptual models or examples where external investment resources are available through (i) centralized coordination power in planned economies or (ii) collateral borrowing in decentralized economies based on the asset value. We characterize equilibrium notion for each case using intuition or simple analytics and graphs, leaving more thorough modeling work and technical proofs to future studies. We also discuss the model's implications.

A. Government coordination power

If the government can provide an additional source of investment fund on a regular basis and help coordination of investment across many different intermediate goods production processes, this situation will definitely facilitate adoption of new technologies. To illustrate, in anticipation of future gains from breakthrough technology, the Chinese government can exercise discretionary power to coordinate distributing capital investment across sectors to create the environment for joint technology adoption. Technically, persistent subsidy expands the output curve (i.e., the production possibility frontier) outward (see Figure 2), so that the condition $Q(m)^{*} \geq Q(m')_{*}$ can now be satisfied, facilitating the adoption of new technologies. As seen in Figure 2, we can view the notation δ_t as some sort of a subsidy rate relative to output in this subsection only. In usual decentralized economies, the government with finite planning horizons (*e.g.*, limited period of governance) does not typically have a sufficient source of funds to allocate across sectors to benefit from technology adoption. Public debts should be managed through the financial markets, and financing further debt is often infeasible because the modern governments barely manage to finance massive welfare expenditures, subject to a severe resource constraint. Nevertheless, a centralized economy can afford to come up with a source of fund to finance technology adoption.

Similarly, we can expand the output curve outward by substantially reducing taxes so that the condition $Q(m)^{*} \geq Q(m')_{*}$ can now be satisfied.[13] Many European economies suffer from high taxes. Without loss of generality, we can express high taxes as shrinking the output curve inward (see Figure 2), so that most of new ideas cannot be commercialized, which can be seen as failing to adopt new technology despite the potential gains from new ideas in the context of our paper.

B. Collateral borrowing: sketching the idea

Now, we attempt to sketch the idea of how collateral lending can provide an additional disposable income and thus help adopt new technologies.[14] First, in each period, individuals make an additional borrowing of $\delta_t \cdot Q_t$, which is expressed as a share δ_t of the current income in period t Q_t, apart from the existing debt based on asset (housing in our context) $v \cdot \varphi Q_t$(see Equation (9) for $\varphi\delta_t$), where v is a certain loan-to-value (LTV) ratio term accepted in the financial sector—the maximum amount of debt permitted by the collateral lending condition. Accordingly, we can define an additional borrowing $\delta_t \cdot Q_t$ which satisfies the following collateral constraint reflecting the LTV ratio:

$$(v\varphi Q_t + \delta_t Q_t)(1+r) = v\varphi Q_{t+1}. \tag{14}$$

This equation gives the simple idea of how housing debt evolves over time at the borrowing rate or r. Now, by using the notation $Q_t^d \equiv (1+\delta_t)Q_t$ and by detrending with the growth rate, we can re-express the housing debt evolution equation as follows:

$$\left(\frac{v\varphi\tilde{Q}_t^d}{1+\delta_t} + \frac{\delta_t\tilde{Q}_t^d}{1+\delta_t}\right)(1+r) = \frac{v\varphi(1+g)\tilde{Q}_{t+1}^d}{1+\delta_t}. \tag{15}$$

From this equation, we can derive the possible value of borrowing share of GDP δ_t as

[13] Taxes were excluded in our simple model, but one can easily extend the model to reflect revenue taxes: the convex output curve shifts inward with higher taxes.

[14] A precise analysis involves some general equilibrium conditions including the collateral constraint as part of the problem. Given that this section is designed to provide an insight, we take a partial analysis for brevity.

$$\delta_t = \nu\varphi \frac{(1+g)(1+g_{t+1})-(1+r)}{(1+r)} \cong \nu\varphi \frac{g+g_{t+1}-r}{(1+r)}, \tag{16}$$

where $1+g_{t+1}=\frac{\tilde{Q}_{t+1}}{\tilde{Q}_t}$ is the output growth rate during the transition path exceeding the steady-state growth rate of g, using the detrended output (see the variables with a tilde sign). In the steady state where housing price grows at a constant rate of g, we have $\delta=\nu\varphi\frac{g-r}{(1+r)}$.

Notably, in each period, agents can take $\delta_t \cdot Q_t$ as an extra income source in addition to output Q_t. $\delta_t Q_t$ in Equation (14) arises from the next period's housing price $[\varphi Q_{t+1}=\varphi(1+g)(1+g_{t+1})Q_t]$, which depends on the next period's income Q_{t+1}, which in turn relies on the expectation of which technology will be adopted in the next period. Thus, if agents believe that new technology will not be adopted in the next period, the economy remains at the steady state of the old technology with a set of low steady state income, housing price, and additional income source. Conversely, if agents believe that new technology will be adopted in the next period which raises the next period income, housing price, and additional income source, they justify its adoption in the relevant self-fulfilling region.

The economic growth rate $g + g_{t+1}$ is higher than the steady state growth rate g as long as the detrended economy is growing in transition to the steady state of new technology, raising capital stock: g_{t+1} is the additional growth owing to the rapid growth during the transition period. The economy at the initial period has been located at the steady state of old technology; thus, the growth rate is at least temporarily greater than $g + g_t > g \Rightarrow g_t > 0$. The economy is either at the steady state of old technology or growing in transition to the steady state of new technology after adopting it.

With the collateral lending condition given above, we can calculate δ_t, the maximum fraction of borrowing to the final output Q_t using equation (14).[15] δ_t is therefore defined as $\delta_t=\frac{g+g_{t+1}-r}{1+r}\nu\varphi$. The condition $g > r$ is required for the existence of equilibrium with collateral

[15] To simplify the analysis, we assume that the economy has been at the steady state from time $t = -\infty$, using the old technology. If banks set the loan-to-value (LTV) ratio at ν, in our model, agents will borrow the maximum amount implied by this ratio. This ratio holds with the equality $\delta_t = [(g+g_{t+1}-r)/(1+r)]\nu\varphi$.

borrowing.[16] This scenario is intuitive: continuous borrowing over time can only be justified at the low borrowing rate.

C. Dynamics with collateral lending

Now, we can discuss the dynamics with collateral using the above equations. We will consider two cases. First, technology adoption does not arise even with the added resources from collateral borrowing. Second, technology adoption becomes successful owing to collateral borrowing. In what follows, the dynamics of final output Q_t and investment/saving for each intermediate good K_t are characterized by Dynamics 2 where technology adoption does not occur despite government intervention or collateral borrowing.[17]

Dynamics 2: The case of borrowing but no technology adoption

$$\begin{aligned}\tilde{Q}_t^d(m) &= (1+\delta_t)\left(\int_0^m \tilde{x}_t(j)^{\frac{\theta-1}{\theta}}dj\right)^{\frac{\theta}{\theta-1}} \\ &= (1+\delta_t)m^{\frac{\theta}{\theta-1}}\tilde{A}_t^{1-\alpha}(\tilde{k}_t-\tilde{f}_m)^{\alpha} \\ &= (1+\delta_t)m^{\frac{\theta}{\theta-1}-\alpha}\tilde{A}_t^{1-\alpha}(\tilde{K}_t-\tilde{f}_m)^{\alpha},\end{aligned} \tag{17}$$

$$\delta_t \cong v\varphi\frac{g+g_{t+1}-r}{(1+r)}, \text{ and at the steady state } \delta \cong v\varphi\frac{g-r}{(1+r)} \textit{ with } g_{t+1}=0. \tag{18}$$

[16] The interest rate for collateral lending is assumed to be the world interest rate in the global financial market with $r < g \leq g_t$. This condition may imply the oversupply of liquidity or credit in the economy, which allows that governments can play a Ponzi debt game, rolling over their debt without ever increasing taxes. However, we do not discuss the issues arising from dynamic inefficiency, because the latter is not the focus of this paper. Additionally, this inequality can hold if the interest rate is artificially lowered by government's industrial policy, or if irrational exuberance pushes up the expected growth rate of economy and asset prices over interest rate. This inequality also happened to Greece, Spain, Ireland, and others immediately after they joined the Eurozone, because their domestic interest rates were higher than the Euro rates.

[17] Here, we assume that individuals believe that collateral borrowing persists indefinitely as long as the collateral lending condition holds, because economic growth rate is greater than the borrowing rate. Even if we assume that firms rather than individuals own the real estate and borrow on this as collateral, main results do not change because firms distribute the returns from borrowed funds to their owners in the form of dividends.

$$k_t = \frac{\beta}{m} Q^d_{t-1}(m) \Rightarrow \tilde{K}_t = \frac{\beta}{1+g} \tilde{Q}^d_{t-1}(m). \tag{19}$$

$$\tilde{Q}^d(m)^* < \tilde{Q}^d(m')_*. \tag{20}$$

Equation (20) implies that at the steady state levels of income and investment, the old technology yields more output than the new technology; thus, the new technology cannot be adopted (see Figure 2). Here, Q^d_t in (20) has an additional δ_t term due to the collateral borrowing. From (17), we can infer that $\delta_t > \delta$ on the convergence path to the steady state, because $g_t > 0$ during the temporary growth path. Figure 2 also describes and compares these dynamics with other dynamics.

A) Dynamics where collateral lending facilitates technology adoption

Now, we characterize the case where collateral lending plays the role of facilitating adoption of a new technology. With the increased disposable income (final output plus collateral lending), it allows greater aggregate demand and output for additional consumption and saving/investment in each period denoted by the red lined curve in Figure 2. Then, we have the following relationship denoted as Dynamics 3.

Dynamics 3: The case of borrowing and technology adoption

$$\begin{aligned} &\tilde{Q}^d_t(m) = (1+\delta_t) m^{\frac{\theta}{\theta-1}} \tilde{A}^{1-\alpha}_t (\tilde{k}_t - \tilde{f}_m)^\alpha = (1+\delta_t) m^{\frac{\theta}{\theta-1}-\alpha} \tilde{A}^{1-\alpha}_t (\tilde{K}_t - m\tilde{f}_m)^\alpha : \\ &\text{under old technology } m, \\ &\tilde{Q}^d_t(m') = (1+\delta_t) m'^{\frac{\theta}{\theta-1}} \tilde{A}^{1-\alpha}_t (\tilde{k}_t - \tilde{f}_{m'})^\alpha = (1+\delta_t) m'^{\frac{\theta}{\theta-1}-\alpha} \tilde{A}^{1-\alpha}_t (\tilde{K}_t - m'\tilde{f}_{m'})^\alpha : \\ &\text{under old technology } m', \end{aligned} \tag{21}$$

$$\delta_t \cong \nu\varphi \frac{g + g_{t+1} - r}{(1+r)}, \tag{22}$$

$$\begin{aligned} &k_t = \frac{\beta}{m} Q^d_{t-1}(m) \;\; or \;\; \tilde{K}_t = \frac{\beta}{1+g} \tilde{Q}^d_{t-1}(m) : \text{under old technology}, \\ &k_t = \frac{\beta}{m'} Q^d_{t-1}(m') \;\; or \;\; \tilde{K}_t = \frac{\beta}{1+g} \tilde{Q}^d_{t-1}(m') : \text{under new technology}, \end{aligned} \tag{23}$$

$$\tilde{Q}^d(m)^* > \tilde{Q}^d(m')_*. \tag{24}$$

Given the inequality $\tilde{Q}^d(m)^* > \tilde{Q}^d(m')_*$, the economy can afford to adopt the new technology with the collateral borrowing allowed (see Figure 2) because the condition (24) implies that at the steady state levels of income and investment (using the old technology), the new technology permits more output production than the old technology. We summarize the discussions above as follows.

Proposition 3: External resources helping technology adoption.
(i) Exercising coordination power in centrally planned economies helps technology adoption. (ii) In decentralized economies, collateral borrowing may help technology adoption.

D. Discussion

Given their general purpose, breakthrough technologies involve massive simultaneous investment across industries for their adoption. In reality, no individual or financial institute can arrange the large funding for investment in big technologies across sectors, although they know the potential income gains from breakthrough technologies (Proposition 1). That is, some firms or industries may launch investment using aggressive entrepreneurship. However, these individual-level efforts end up being short of a big push required for technology adoption, creating a classic coordination problem in technology adoption.

The ways to deal with the coordination problem may differ across economies. Centralized economies with coordination power (*e.g.*, China) can successfully handle the thorny coordination issues by exercising discretionary power and mobilizing investment resources for technology adoption. Consequently, they often become technology leaders in the modern decades. Most decentralized economies with highly developed financial markets can also suffer from a different kind of the coordination problem due to a lack of investment fund. None can finance fixed costs out of nothing, especially for large fixed investments necessary for technology adoption. In this case, collateral borrowing can be a useful method to provide additional investment sources for technology adoption. The asset price increases rapidly when agents know that adopting new big technology is possible with sufficient funding at a low borrowing rate and when the collateral constraint permits borrowing. Then, agents may afford to make large investment, resolving the coordination problem mentioned above.

We contrast the two different ways of resolving the coordination problem. The implication for the decentralized economies may sound a bit controversial, but we need to be cautious on evaluating bubbles. Generally, bubbles are socially bad but may be justified in certain instances when pertaining to the asset bubbles forming with innovative technological changes because bubbles may resolve the coordination problem.

Meanwhile, the current so-called 4^{th} industrial revolution technologies are based on ICT and many labor-saving features with several commercial applicabilities. In addition, COVID-19 provides a favorable environment where these big technologies are very useful for handling online transactions. Furthermore, the low borrowing cost (*e.g.*, a zero lower bound) combined with vast supply of government subsidies may help introduce these technologies by resolving the coordination problem mentioned throughout the paper.

IV. Summary and conclusions

This research has examined the fundamental issue why adopting breakthrough technologies is difficult, despite the obvious potential gains from adopting new innovative technologies. We have highlighted the insight that new innovative technologies involve not only a handful of sectors but nearly all sectors in an economy to jointly make large fixed infrastructure investment, which is prohibitively costly. Such fixed costs have to be financed across all different sectors given the nature of influential technologies. If only a few sectors make investment but the rest do not, the new innovative technology cannot take root in an economy. Therefore, we have shown that financing the large fixed costs is essential in adopting new technologies. Therefore, the notion of coordination across subsectors is important, especially when the financial markets are less developed, not to mention the large investment resources, which are usually difficult to obtain even under developed financial markets.

Centralized economies with coordination power can successfully handle the thorny coordination issues by exercising discretionary power and mobilizing investment resources for technology adoption.

Accordingly, they often become technology leaders in the modern decades. Decentralized economies with highly developed financial markets can also suffer from coordination problem due to a lack of investment fund. In this case, collateral borrowing can be a useful method to provide additional investment sources for technology adoption.

We have constructed a growth model of technology adoption. Then, by incorporating coordination power and/or collateral lending into a simple growth model, we show that coordination power in centralized economies and/or collateral lending in decentralized ones can boost aggregate demand, facilitating the adoption of new technologies. Once a threshold level of investment is funded, the increasing returns to scale property arising from fixed costs generates a dynamic path toward a stable equilibrium with high output.

This study presents some straightforward policy implications. First, markets for adopting innovative technologies are missing. Private markets may not perfectly handle technology adoption for coordination issues and lack of resources given the convexity created by the large fixed costs. Second, proper policy interventions at the government level can often be justified. Third, collateral borrowing in the period of new innovative technology development might be warranted for social welfare.

We also acknowledge the remaining caveats in the model. (i) Our model lacks elaborate features such as uncertainty. (ii) A more detailed analysis of coordination issues and collateral lending seems warranted. (iii) Adding further realism to the model can help provide more realistic implications. Future research agenda may include the revisions along the lines of these issues.

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Appendix A. Conditions for existence of multiple equilibria

We derive the conditions for existence of multiple equilibria. Technically, given the functional forms of Equations (12) and (13), two possible solutions can satisfy the equations. As in the text, we detrend all growing endogenous variables including final output, intermediate goods, and investment over a constant growth path with a growth rate of $g_t = g$.

From Figure 1, we can easily derive the condition for the existence of multiple equilibria (A1) and the condition for a unique equilibrium (A2), respectively, as follows:

$$Z = m^{\frac{\theta}{\theta-1}-\alpha}\tilde{A}^{1-\alpha}(\tilde{K}_t - m\tilde{f}_m)^{\alpha} - \frac{1+g}{\beta}\tilde{K}_t > 0, \tag{A1}$$

$$Z = m^{\frac{\theta}{\theta-1}-\alpha}\tilde{A}^{1-\alpha}(\tilde{K}_t - m\tilde{f}_m)^{\alpha} - \frac{1+g}{\beta}\tilde{K}_t = 0. \tag{A2}$$

Henceforth, we use the notation $A = \tilde{A}^{1-\alpha}$ to simplify the equations. By taking a derivative of (A1) with respect to $\tilde{K}_t$ and setting it to equals zero, we find that, at $\tilde{K}^* = \left(\beta'\alpha m^{\frac{\theta}{\theta-1}-\alpha}A\right)^{1/(1-\alpha)} + m\tilde{f}_m$, Z in (A1) and (A2) has the maximum value. Substituting $\tilde{K}^* = \left(\alpha^{\frac{\alpha}{1-\alpha}} - \alpha^{\frac{1}{\alpha}}\right)^{1/(1-\alpha)} + m\tilde{f}_m$ into Z in (A1) and (A2), we obtain the condition for the existence of two solutions: one with $Z > 0$ and the other with $Z = 0$:

$$Z^* = \left(\frac{\beta}{1+g}\right)^{\frac{1}{1-\alpha}}\left(\alpha^{\frac{\alpha}{1-\alpha}} - \alpha^{\frac{1}{\alpha}}\right)\left(Am^{\frac{\theta}{\theta-1}-\alpha}\right)^{\frac{1}{1-\alpha}} \geq \tilde{f}_m \cdot m. \tag{A3}$$

Determining the exact condition for (A3) to hold is not simple. Given the form $f_m = (1+g)^t cm^{\mu}$, where c grows with a growth rate of g; then, from (A3), we can derive the following sufficient conditions for the existence of two solutions. The idea is that when both the exponent and coefficient of m in the LHS term in inequality (A3) are greater than the RHS term counterparts, the whole term (A3) is constantly positive, *i.e.*, sufficient conditions.

$$\frac{\theta + \frac{\alpha}{\alpha - 1}}{\theta - 1} > 1 + \mu, \ \ and \tag{A4}$$

$$\left(\frac{\beta}{1+g}\right)^{\frac{1}{1-\alpha}} A^{\frac{1}{1-\alpha}} \left(\alpha^{\frac{\alpha}{1-\alpha}} - \alpha^{\frac{1}{\alpha}}\right) \geq \tilde{c}. \tag{A5}$$

Appendix B. Further discussion of technology non-adoption: $Q(m)^* < Q(m')_*$

We derive a more specific parameter condition for the inequality $Q(m)^* < Q(m')_*$ to hold. As in Appendix A, we also apply a similar detrending at a growth rate of g. Here, all variables are detrended, and we set $A = \tilde{A}^{1-\alpha}$ to simplify the expressions.

From (12) and (13), the stable steady state equilibrium satisfies the two conditions, $Q(m)^* = m^{\frac{\theta}{\theta-1}-\alpha} A(K(m)^* - mf_m)^\alpha$ and $K(m)^* = \beta Q(m)^* / (1+g)$. The second equation can be rearranged to $Q(m)^* = (1+g)K(m)^*/\beta$. We can also easily infer that if $Q(m)^* < Q(m')_*$, $=\bar{K}(m')$ exists and thus satisfies the following (see Figure 2):

$$Q(m)^* = m^{\frac{\theta}{\theta-1}-\alpha} A(K(m)^* - mf_m)^\alpha = m'^{\frac{\theta}{\theta-1}-\alpha} A(\bar{K}(m') - m'f_{m'})^{\alpha}. \tag{B1}$$

Meanwhile, we can also define the point $\hat{K}(m')$ in Figure 2 that satisfies

$$Q(m)^* = (1+g)\frac{1}{\beta} K(m)^* = (1+g)\frac{1}{\beta}\hat{K}(m'). \tag{B2}$$

As Figure 2 shows, $\bar{K}(m')$ is larger than $\hat{K}(m')$, which is in fact equivalent to the condition for technology non-adoption, $Q(m)^* < Q(m')_*$—only under the condition $Q(m)^* < Q(m')_*$ and the specific curvatures of (12) and (13) as in Figure 2, the inequality $\bar{K}(m') > \hat{K}(m')$ holds.

Rearranging the second equality in equations (B1) gives $\bar{K}(m') - m'f_{m'} = \left(\frac{m}{m'}\right)^{\frac{\theta}{\alpha(\theta-1)}-1} [K(m)^* - mf_m]$ (the left-hand side of [B3] below) while rearranging the second equality in equations (B2) gives $K(m)^* > \hat{K}(m')$ (the right-hand side of [B3] below). Given that $\bar{K}(m') > \hat{K}(m')$ and $m'f_{m'} = mf_m$, we can derive the following inequality required for non-adoption:

$$\bar{K}(m') = \left(\frac{m}{m'}\right)^{\frac{\theta}{\alpha(\theta-1)}-1} (K(m)^* - mf_m) + m'f_{m'} > \hat{K}(m') = K(m)^*. \tag{B3}$$

Rearranging (B3) gives the following:

$$\left(\frac{m}{m'}\right)^{\frac{\theta}{\alpha(\theta-1)}-1}[K(m)^{*}-mf_{m}]+m'f_{m'}-K(m)^{*}>0$$
$$\leftrightarrow [1-\left(\frac{m}{m'}\right)^{\frac{\theta}{\alpha(\theta-1)}-1}(m'f_{m'}-\left(\frac{m}{m'}\right)^{\frac{\theta}{\alpha(\theta-1)}-1}mf_{m}]>K(m)^{*}, \quad \text{(B4)}$$

where $m'>m$ and $\frac{\theta}{\alpha(\theta-1)}>1$. This condition is necessary and sufficient for $Q(m)^{*}<Q(m')_{*}$ [or $\bar{K}(m')>\hat{K}(m')$]. Here is the intuition behind the condition. Given the set of parameters $\{m, f_m, f_{m'}, \alpha, \text{and } \theta\}$, the new technology m' is not adopted; if the technological change, $m'-m$, is too big [if so, LHS of (B4) converges to $m'f_{m'}$.] and/or the fixed cost constitutes a large fraction of capital (if so, the term $f_{m'}$ dominates.).

Appendix C. Solving the model

We present further details of our model including general equilibrium and its key features. Given that agents' behaviors were already described in Section II, here, we show how to solve the model and describe some notable features.

The derivation of the model's equilibrium follows the routine of the basic Romer model. Here, all variables are detrended, and we set $A=\tilde{A}^{1-\alpha}$ to simplify the expressions. Given the intermediate good prices $\{q_t(j)\}$ and technology m, the final good producer maximizes her profit π^f by optimally choosing intermediate goods as input:

A. Optimization

$$\underset{\{x_t(j)\}}{Max}\ \pi^{f}=[\int_0^m x_t(j)^{\frac{\theta-1}{\theta}}dj]^{\frac{\theta}{\theta-1}}-\int_0^m q_t(j)x_t(j)dj. \quad \text{(C1)}$$

Then, the demand functions for intermediate goods are derived from the FOCs of (C1) with respect to $\{x_t(j)\}$ as

$$\left(\int_0^m x_t(j)^{\frac{\theta-1}{\theta}}dj\right)^{\frac{1}{\theta-1}}x_t(j)^{-\frac{1}{\theta}}-q_t(j)=0. \quad \text{(C2)}$$

Given the CRS technology, profits do not arise, implying $Q_t=m^{\frac{\theta}{\theta-1}}x_t$.

Now, we consider the intermediate good producers' problem. Given the price of investment goods p_t, an intermediate good producer maximizes her profit $\pi^i[x_t(j)]$ by

$$\begin{aligned}\underset{x_t(j)}{Max}\ \pi^i[x_t(j)] &= q_t(j)x_t(j) - p_t k_t(j) \\ &= q_t(j)x_t(j) - p_t(A^{-1/\alpha}x_t(j)^{1/\alpha} + f_m m) \quad (\because (2)) \\ &= \left[\int_0^m x_t(j)^{\frac{\theta-1}{\theta}} dj\right]^{\frac{1}{\theta-1}} x_t(j)^{\frac{\theta-1}{\theta}} - p_t(A^{-1/\alpha})x_t(j)^{1/\alpha} + f_m m, \ (\because (C2)),\end{aligned}$$

where the second line made use of equation (2) $k_t(j) = A^{-1/\alpha}x_t(j)^{1/\alpha} + f_m m$, and the third line made use of (C2). Notably, the intermediate good producer determines a profit-maximizing quantity by considering the demand for its product. Then, FOC of (C3) with respect to $x_t(j)$ gives

$$\frac{\theta-1}{\theta}\left[\int_0^m x_t(j)^{\frac{\theta-1}{\theta}} dj\right]^{\frac{1}{\theta-1}} x_t(j)^{-\frac{1}{\theta}} - \frac{1}{\alpha} p_t A^{-\frac{1}{\alpha}} x_t(j)^{\frac{1-\alpha}{\alpha}} = 0. \tag{C4}$$

Meanwhile, the general equilibrium condition that saving equals investment yields

$$k_t(j) = \frac{1}{m} Q_{t-1}\beta. \tag{C5}$$

Plugging (C5) into the last expression in equation (3) gives

$$Q_t = m^{\frac{\theta}{\theta-1}} A_t[k_t(j) - f_m]^\alpha = m^{\frac{\theta}{\theta-1}} A_t(\frac{1}{m} Q_{t-1}\beta - f_m)^\alpha. \tag{C6}$$

Equation (C4) describes some sort of a supply function for $x_t(j)$ [thus, for $k_t(j)$] given the investment good price p_t (*i, e., user cost of capital*) and the general equilibrium condition of $k_t(j) = (Q_{t-1}\beta)/m$. Plugging $x_t(j) = A_t \cdot (k_t(j) - f_m)^\alpha = A_t \cdot (\frac{1}{m} Q_{t-1}\beta - f_m)^\alpha$ into (C4), we can solve for p_t. Then, multiplying $x_t(j)$ and taking an integral over $j \in [0, m]$ on both sides of (C4) delivers

$$\frac{\theta-1}{\theta}\left(\int_0^m x_t(j)^{\frac{\theta-1}{\theta}} dj\right)^{\frac{\theta}{\theta-1}} \equiv \frac{\theta-1}{\theta} Q_t = p_t \frac{1}{\alpha} A^{-\frac{1}{\alpha}} \int_0^m x_t(j)^{\frac{1}{\alpha}} dj. \tag{C7}$$

Substituting (C6) $Q_t = m^{\frac{\theta}{\theta-1}} A_t \left(\frac{1}{m} Q_{t-1}\beta - f_m \right)^{\alpha}$ into (C7) of $\frac{\theta-1}{\theta} Q_t = p_t \frac{1}{\alpha} A^{-\frac{1}{\alpha}} \int_0^m x_t(j)^{\frac{1}{\alpha}} dj$ together with $x_t(j) = A_t \cdot \left(\frac{1}{m} Q_{t-1}\beta - f_m \right)^{\alpha}$ gives the price of investment goods:

$$p_t = \frac{\alpha(\theta-1)}{\theta} A_t m^{\frac{1}{\theta-1}} \left(\frac{1}{m} Q_{t-1}\beta - f_m \right)^{\alpha-1}. \tag{C8}$$

Similarly, plugging $x_t(j) = A_t \cdot \left(\frac{1}{m} Q_{t-1}\beta - f_m \right)^{\alpha}$ into (C2) yields the price of intermediate goods:

$$q_t = m^{\frac{1}{\theta-1}} \tag{C9}$$

This result is quite obvious, because $Q_t = m^{\frac{\theta}{\theta-1}} x_t$ (*i.e.*, $Q_t = m \cdot q_t x_t$).[18]

B. General equilibrium

Now, we can define the general equilibrium for our model in the following way. First, given A, m and f_m, we can define the prices of intermediate goods $\{q_t(j)\}$. Second, the equilibrium quantities of $\{x_t(j)\}$ can be obtained from (C2). Third, output Q_t is determined by $Q_t = m^{\frac{\theta}{\theta-1}} x_t(j)$. Fourth, using the equation $k_t(j) = (Q_{t-1}\beta)/m$, we can determine the investment quantities $\{k_t(j)\}$. Finally, the price of investment p_t is obtained from (C8).

We solve for the total payment to capital and the total profits, which are given by (C10) and (C11), respectively, as follows: we combine Equations (C3), (C7), and (C8) to obtain the following:

$$\begin{aligned}
\int_0^m p_t k_t(j) dj &= p_t m k_t \\
&= \frac{\alpha(\theta-1)}{\theta} A_t m^{\frac{1}{\theta-1}} \left(\frac{1}{m} Q_{t-1}\beta - f_m \right)^{\alpha-1} Q_{t-1}\beta \\
&= \frac{\alpha(\theta-1)}{\theta} A_t m^{\frac{1}{\theta-1}} \left(\frac{1}{m} Q_{t-1}\beta - f_m \right)^{\alpha} \frac{Q_{t-1}\beta}{Q_{t-1}\beta - m f_m} \\
&= Q_t(m) \frac{\alpha(\theta-1)}{\theta} \frac{Q_{t-1}\beta}{Q_{t-1}\beta - m f_m}
\end{aligned} \tag{C10}$$

[18] See the zero profit condition in (C1).

and

$$\int_0^m \pi^i(x_t(j))dj = Q_t - \int_0^m p_t k_t(j)dj$$

$$= A_t m^{\frac{\theta}{\theta-1}} \left(\frac{1}{m} Q_{t-1}\beta - f_m\right)^{\alpha} - \frac{\alpha(\theta-1)}{\theta} A_t m^{\frac{1}{\theta-1}} \left(\frac{1}{m} Q_{t-1}\beta' - f_m\right)^{\alpha-1} Q_{t-1}\beta$$

$$= A_t m^{\frac{\theta}{\theta-1}} \left(\frac{1}{m} Q_{t-1}\beta - f_m\right)^{\alpha} \left[1 - \frac{\alpha(\theta-1)}{\theta} \frac{Q_{t-1}\beta}{Q_{t-1}\beta - mf_m}\right] \quad \text{(C11)}$$

$$= A_t m^{\frac{\theta}{\theta-1}-\alpha} \left(Q_{t-1}\beta - mf_m\right)^{\alpha} \left[1 - \frac{\alpha(\theta-1)}{\theta} \frac{Q_{t-1}\beta}{Q_{t-1}\beta - mf_m}\right]$$

$$= Q_t(m) \left[1 - \frac{\alpha(\theta-1)}{\theta} \frac{Q_{t-1}\beta}{Q_{t-1}\beta - mf_m}\right].$$

Although each of these two looks complex, the sum of the two is simply final output $Q_t = \int_0^m p_t k_t(j)dj + \int_0^m \pi\left[x_t(j)dj\right]$.

References

Aghion, P., Howitt, P., and Mayer-Foulkes, D. "The effect of financial development on convergence: Theory and evidence." *Quarterly Journal of Economics* 120(No. 1 2005): 173-222.

Baily, M. N., and Lawrence, R. Z. "Do We Have a New E-Economy?" *American Economic Review* 91(No. 2 2001): 1308-312.

Bircan, C. and De Hass, R. "The Limits of Lending? Banks and Technology Adoption across Russia, *Review of Financial Studies* 33(No. 2 2020): 536-609.

Cochrane, J. H. *Stocks as Money: Convenience Yield and the Tech-Stock Bubble.* **NBER Working Paper #8987, 2002.**

De Long J.B. and Shleifer, A. "The Stock Market Bubble of 1929: Evidence from Closed-end Mutual Funds," *Journal of Economic History* 51(1991): 675-700.

Fisher, I. 1930. *The Stock Market Crash - and After*. New York: Macmillan.

Friedman, M. and Schwartz, A. J. *A Monetary History of the United States,* 1867–1960, Princeton University Press, 1963.

Hirano, T., and Yanagawa, N. "Asset Bubbles, Endogenous Growth, and

Financial Frictions," *The Review of Economic Studies* 84(No. 1 2017): 406.

Jorgenson, Dale W. "Information Technology and the U.S. Economy." *American Economic Review* 91(No. 12 2001): 1-32.

Jovanovic, B., and Rousseau, P. L. *Why Wait? A Century of Life Before IPO.* NBER Working Paper 8081, 2001.

Justiniano, A., Primiceri, G. E., and Tambalotti, A. *The Effects of the Saving and Banking Glut on the U.S. Economy*, Federal Reserve Bank of New York Staff Reports, # 648, 2013.

Kashyap, A., Scharfstein, D., and Weil, D. *The high price of land and the low cost of capital: theory and evidence from Japan.* MIT Working Paper, 1993.

Keynes, J. M., *The General Theory of Employment, Interest and Money*, London: Macmillan, 1936(reprinted, 2007).

Kim, Y. J., and Lee, J-W. "A Model of Self-fulfilling Financial Crises." *Japanese Economic Review* 57(2006): 87-100.

Kim, Y. J., and Lee, J-W. "Over-investment, Collateral Lending, and Economic Crisis." *Japan and the World Economy* 14(2002): 181-201.

Kim, Y. J. and Lee C.-I., "Sovereign Debt Crisis in a Monetary Union: Accounting For Excessive Debt, Housing Bubbles, And The Transmission Of Crises," *Economic Inquiry* 57(No.2 2019): 1098-1119.

Kindleberger, C. P. *Manias, Panics and Crashes: A History of Financial Crises*. Third Edition, John Wiley & Sons, Inc., 1996

Kindleberger, C. P. *The World in Depression*. University of California Press, Berkeley/USA, 1986

Kiyotaki N., and Moore, J. "Credit Cycles," *Journal of Political Economy* 105(No. 2 1997): 211-248.

Long, J. B. and Plosser, C. "Real Business Cycles," *Journal of Political Economy* 91(No. 1 1983): 36-69.

Mankiw, N. G., Romer, D., and Weil, D. N. "A contribution to the empirics of economic growth." *Quarterly Journal of Economics* 107(1992):407-437.

Miao, J. "Introduction to Economic Theory of Bubbles," *Journal of Mathematical Economics* 53(2014): 130-136.

Miao, J. and Wang, P. "Bubbles and Total Factor Productivity," *American Economic Review* 102(No. 3 2012): 82-87.

Miao, J. and Wang, P. "Sectoral Bubbles, Misallocation, and Endogenous

Growth," *Journal of Mathematical Economics* 53(2014): 153-163.
Miao, J. and Wang, P. "Banking Bubbles and Financial Crises," *Journal of Economic Theory* 157(2015): 763-792.
Morck, R., *Kindleberger Cycles and Economic Growth: Method in the Madness of Crowds?,* NBER Working Paper # 28411, 2021.
Ramsey, E., "A mathematical theory of saving," *Economic Journal* 88(1928):543-559.
McGrattan, E. R., and Prescott, E. C. *Unmeasured Investment and the 1990s U.S. Hours Boom*, Research Department Staff Report 369, Federal Reserve Bank of Minneapolis, June, 2006.
McGrattan, E. R., and Prescott, E. C. "Taxes, Regulations, and the Value of U.S. and U.K. Corporations," *Review of Economic Studies* 72(2005): 767-796.
McGrattan, E. R., and Prescott, E. C. *The Stock Market Crash of 1929: Irving Fisher Was Right!*, Federal Reserve Bank of Minneapolis Research Department Staff Report 294 (NBER Working Paper 8622), 2003.
McGrattan, E. R., and Prescott, E. C. "Is the Stock Market Overvalued?,"*Federal Reserve Bank of Minneapolis Quarterly Review* 24(No. 4 2000): 20–40.
Minsky, H. P. *Financial Instability and the Decline (?) Of Banking: Public Policy Implications.* Bank Structure and Competition, Federal Reserve Bank of Chicago, May, 1994.
Minsky, H. P. "Banking and Industry between the Two World Wars: The United States." *Journal of European Economic History* 13(No.2 1984): 235-272.
Minsky, H. P. "Can 'It' Happen Again?" in *Banking and Monetary Studies* (Deanne Carson, ed.), Homewood, IL: Richard D. Irwin, Inc, 1963.
Minsky, H. P. "Monetary Systems and Accelerator Models," *American Economic Review* 47(1957): 860-883.
Murphy, K. M., Shleifer, A., and Vishny, R. W. "Industrialization and the Big Push." *Journal of Political Economy* 97(No. 5 1989): 1003-1026.
Ohanian, Lee E. "Why Did Productivity Fall So Much During the Great Depression?" *American Economic Review* 91(No. 2 2001): 34-38.
Rappoport, P. and White, E. N. "Was There a Bubble in the 1929 Stock Market?" *Journal of Economic History* 53(1993): 549-574.
Roller, L. H., and Waverman, L., "Telecommunications Infrastructure

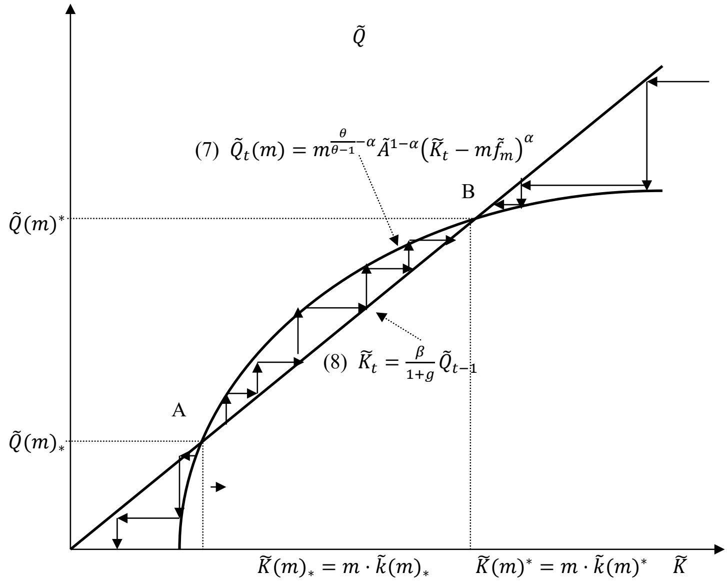
and Economic Development: A Simultaneous Approach." *American Economic Review* 91(No. 4 2001): 909-923.

Romer, P. M. "Endogenous Technological Change." *Journal of Political Economy* 98(1990): S71-S101.

Romer, P. M. "Increasing Returns and Long-Run Growth." *Journal of Political Economy* 94(1986): 1002-1037.

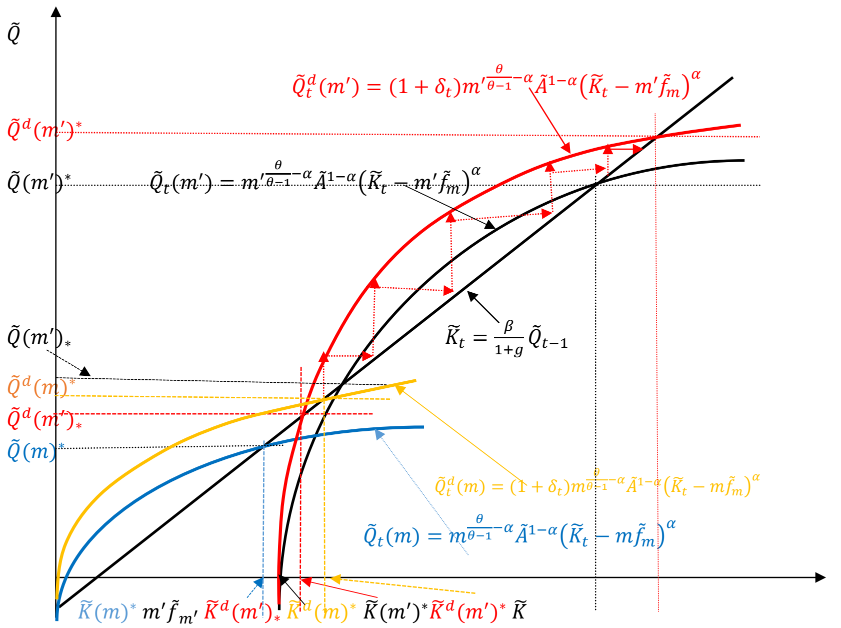
Smith, W. T. "A Closed Form Solution to the Ramsey Model." *The BE Journal of Macroeconomics 6*(No. 1 2006): 1-27

Temin, P. *Lessons from the Great Depression.* MIT Press, 1989



Note: (i) $\tilde{Q}$ and $\tilde{K}$ are detrended output and capital. (ii) Point A of $\{\tilde{Q}(m)^*, \tilde{K}(m)^*\}$ represents a unique pair of the stable steady state levels of final output and investment under the use of the old technology. Point B of $\{\tilde{Q}(m)_*, \tilde{K}(m)_*\}$ is unstable equilibrium. (iii) In transition from point A to B, the growth rate can exceed the steady state growth rate, implying a temporary growth effect.

Figure 1
Dynamics of Final Output and Investment



Note: (i) $\tilde{Q}_t^d$ = detrended output based on collateral borrowing. (ii) Two curves on the lower left corner indicate output using old tech m. The higher right counterparts indicate output using new tech m'. (iii) The dashed arrow represents the dynamics of capital and output when collateral borrowing boosts output and investment, such that new technology is adopted under the condition of $\tilde{Q}^d(m')_* < \tilde{Q}^d(m)^*$.

Figure 2
Technology Adoption vs. Non-Adoption