A Theory of Total Factor Productivity and the Convergence Hypothesis: Workers' Innovations as an Essential Element

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Workers' Innovations as an Essential Element

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Abstract

A theory of total factor productivity (TFP) is needed to explain why substantial differences in international income have been observed. This paper presents a theory of TFP that incorporates workers' innovations. Because workers are human and capable of creative intellectual activities, they can create innovations even if these innovations are minor. The creative activities of ordinary workers have been almost entirely neglected in economics even though the importance of workers' learning activities has been emphasized by the theories of learning-by-doing and human capital. I examine this creative element and show that innovations created by ordinary workers are indispensable for efficient production. A production function incorporating workers' innovations is shown to have a Cobb-Douglas functional form with a labor share of about 70%. The production function offers a microfoundation of the Cobb-Douglas production function and more importantly indicates that heterogeneous parameter values with regard to workers' innovations are essential factors of the currently observed substantial income difference across economies.

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1 INTRODUCTION

Innovations are usually presumed to be created only by researchers and other highly educated or trained employees, and this bounded nature of innovation has been explicitly or implicitly assumed in most economic analyses. However, conceptually, innovations are not necessarily only created by researchers and other highly educated or trained employees. *The American Heritage Dictionary of the English Language* (Fourth Edition) defines innovation as “the act of introducing something new” or “something newly introduced.” At its core, therefore, innovation does not exclude things or processes created by “ordinary” workers. The question, however, is whether workers who are not well educated or highly trained can really create something new. The answer to that question is yes, even if most of the innovations are minor, because workers are human and therefore have the ability to create. A robot or a machine can deal with preprogrammed tasks quite well if nothing unexpected occurs, but if an unexpected problem occurs, the machine may immediately stop working properly even if the problem is relatively minor. Moreover, the machine not only will stop working properly but also will be unable to fix the unexpected problem by itself. Only human beings can fix unexpected problems by creating something new, or innovating. Because workers are not machines but human, they can fix unexpected, even if only minor, problems by innovating.

Emphasizing the importance of workers’ roles in production processes is not a new idea. Arrow’s (1962) learning-by-doing theory argues that productivity is improved by workers’ regularly repeating the same type of action. The concept of learning-by-doing has been applied to many fields in economics (e.g., Sheshinski, 1967; Hall and Howell, 1985; Romer, 1986; Adler and Clark, 1991; Nemet, 2006). In addition, the importance of human capital has been argued since Mincer (1958) and Becker (1962, 1964). Human capital is similar to physical capital and substitutable for physical capital and labor. Both theories (learning-by-doing and human capital) stress that workers’ activities play an important role in production processes, particularly that they are important for economic growth because skills or techniques obtained through learning-by-doing or human capital obtained by training or education accumulate, and accumulated worker knowledge or human capital enhances economic growth. Nevertheless, theories of learning-by-doing and human capital focus almost exclusively on workers acquiring pre-existing knowledge. The idea that workers can also create something new (i.e., innovate) has drawn little attention; in fact, it has been neglected in economics. However, as argued above, workers can innovate even if most of the innovations are minor. The existence of this ability indicates that it is rational for firms to fully exploit the opportunities that workers’ creative activities offer. Rational firms will offer incentives for their workers to create innovations. This rational behavior will have a variety of impacts on economic activities. In this paper, I examine the mechanism and importance of the creative activities of ordinary workers in production processes.

Innovations have been regarded to be naturally accumulative, which may be why workers’ innovations have been neglected. It may seem natural to conjecture that, even if workers can innovate, their innovations have no value because they are minor, unrecorded, and not transferred; that is, they do not accumulate as part of human common knowledge. In this paper, I offer an alternative view that non-accumulative innovations created by ordinary workers are indispensable for efficient production because (1) accumulated knowledge is far from perfect and (2) the division of labor generates incomplete information sharing. These imperfections (imperfect knowledge and incomplete information) generate many unexpected problems and require ordinary workers to innovate. It is difficult to question the imperfect state of current knowledge. Intensive research activities have been and will continue to be conducted because scientific knowledge is imperfect and incomplete. Since accumulated knowledge is imperfect, many minor and unexpected problems routinely occur in production processes, and workers must create minor innovations so that the machines that have been built using imperfect knowledge can operate. In addition, the division of labor divides information on the entire production process among workers. This fragmentation of information brings about many unexpected problems and thus creates production inefficiencies, some of which can be reduced by workers' innovations at each production site.

The experience curve effect, which states that the cost of doing a task will decrease as the task is performed more often, explains the generation mechanism of workers' innovations to some extent. The primary idea of the experience curve effect (called the "learning curve effect" in early literature) dates back to Wright (1936), Hirsch (1952), Alchian (1963), and Rapping (1965). The importance of the learning curve effect was emphasized by the Boston Consulting Group (BCG) in the late 1960s and early 1970s (e.g., BCG, 1972). The experience (or learning) curve effect has been applied in many research fields, including business management, strategy, and organizational studies (e.g., Searle and Goody, 1945; Asher, 1956; Dudley, 1972; Joskow and Rozanski, 1979; Zimmerman, 1982; Womer and Patterson, 1983; Lieberman, 1984; Argote et al., 1990; Reis, 1991). More recently, it has been applied to study technology and policy analysis, particularly for application to energy technologies (e.g., Yelle 1979; Dutton and Thomas, 1984; Hall and Howell, 1985; Lieberman, 1987; Argote and Epple, 1990; Criqui et al., 2000; McDonald and Schrattenholzer, 2001; van der Zwaan and Rablc, 2003, 2004; Miketa and Schrattenholzer, 2004; Papineau, 2006). In this paper, I apply the experience curve effect to the generation mechanism of workers' innovations, in particular, innovations to supplement imperfect accumulative innovations and to reduce the inefficiency in information sharing resulting from the division of labor.

A production function that incorporates workers' innovations, the generation mechanism of which is described by the experience curve effect, is induced. This production function is consistent with production functions that have been used in many analyses in that it has a Cobb-Douglas functional form, with a labor share of about 70% and strict Harrod neutrality. Conversely, incorporating workers' innovations provides an alternative rationale for the important properties adopted in many production functions that are usually used; in particular, it provides a microfoundation of the Cobb-Douglas production function. Nevertheless, the most important nature of this production function is not that it is consistent with conventional production functions or that it provides a microfoundation of the Cobb-Douglas production function but that it provides an important clue for judging the validity of the convergence hypothesis in growth economics. The convergence hypothesis states that GDP per capita values that are currently significantly heterogeneous across economies will converge at a unique identical level in the long run. The convergence is naturally predicted by neo-classical

Ramsey growth models. On the other hand, many endogenous growth models do not support the convergence hypothesis (e.g., Romer, 1986, 1987; Lucas, 1988). The conclusions of empirical studies are mixed and inconclusive (e.g., Abramovitz, 1986; Baumol, 1986; Barro, 1991; Barro and Sala-i-Martin, 1992; Mankiw et al., 1992; Bernard and Durlauf, 1995; Jones, 1997; Michelacci and Zaffaroni, 2000; Cheung and Garcia-Pascual, 2004). Prescott (1998) concludes that a theory of total factor productivity (TFP) is needed to solve this problem. The production function that is induced in this paper by incorporating workers' innovations indicates that whether income levels converge internationally or not is determined by each economy's structural parameter values with regard to workers' innovations as well as those with regard to institutions, particularly institutional aspects of government and the financial sector. If one of these parameters is heterogeneous, the convergence in per capita GDP is not necessarily predicted.

The paper is organized as follows. In Section 2, I examine the nature of workers' innovations and show that ordinary workers can create innovations although their innovations are minor. I also demonstrate that these innovations are indispensable for efficient production because imperfect accumulative innovations and fragmented and incomplete information cause unexpected problems and inefficiencies. In Section 3, the experience curve effect is applied to workers' innovations, particularly non-accumulative innovations to supplement imperfect accumulated innovations and fragmented and incomplete information. In Section 4, a production function that incorporates workers' innovations with the experience curve effect is induced. This production function provides an alternative rationale and microfoundation of the Cobb-Douglas functional form and has a labor share of about 70% and strict Harrod neutrality. In Section 5, on the basis of the production function, I show that heterogeneous parameter values with respect to workers' innovations and institutions are essential factors of the currently observed substantial income difference across economies. Finally, I offer concluding remarks in Section 6.

2 WORKERS' INNOVATIONS

2.1 Non-accumulative innovation

2.1.1 Innovations need not be intrinsically accumulative

Innovations are usually considered to be intrinsically accumulative, and TFP reflects the total sum of innovations that have been created and accumulated in the long history of human beings. However, accumulativeness is not a necessary condition for innovation because, as discussed in the introduction, its core meaning is the act of introducing something new or the thing itself that has been newly introduced. Luecke and Katz (2003) argue that innovation is generally understood as the introduction of a new thing or method and the embodiment, combination, or synthesis of knowledge in original, relevant, valued new products, processes, or services. The essence of innovation is therefore not accumulativeness but newness.

Nevertheless, non-accumulative innovations have drawn little or no attention in economics because innovations that are not accumulated have been regarded as being without value from an economic point of view. Accumulated innovations are often thought of as knowledge or technology, and they are usually regarded as equivalent to

TFP. An innovation that is not accumulated is not included as knowledge, technology, or TFP because these must be commonly accessible and non-accumulative innovations are not. From this perspective, non-accumulated innovations are considered to have no effect on production and therefore be meaningless. The neglect of non-accumulative innovation may also be partially attributed to the belief that innovations must be accumulated because they have the innate nature of spillover (i.e., transfer), which implies accumulation. If an innovation makes someone better off, rational people have incentive to obtain and utilize it; thus, the innovation spills over. To spill over, the innovation must be recorded and transferrable in advance, that is, accumulated as a common piece of knowledge or technology. Conversely, innovations must be accumulated if they are consistent with the incentives of rational people.

However, the above rationales do not necessarily hold, for the following reason. A non-accumulative innovation is without value to people who did not create it, and the above rationales are convincing if only those people are considered. There is, however, no *a priori* reason that a non-accumulative innovation is valueless to the person who created it because that person can utilize it personally for production even if others cannot. Therefore, even if an innovation is not accumulated and does not become common knowledge, it still can contribute to production. A non-accumulative innovation may even be an important production element for the person who created it. In addition, if the costs to acquire an innovation created by other persons are higher than its benefits, the innovation will not spill over. Therefore, the concept that some innovations do not spill over and are not accumulated is not inconsistent with rational people's incentives for using innovations. Clearly the accumulativeness of innovation is not a simple issue and requires more careful consideration.

2.1.2 Innovations that are not accumulated

Innovations will be used personally even if they are not recognized and recorded. In addition, some innovations may be deliberately kept personal. Hence, an innovation will not be accumulated if nobody is aware of the innovation's novelty, nobody records or reports the innovation, or the person who created the innovation keeps it secret. The above conditions will be satisfied in the following situations. An innovation will not be recognized or recorded if the innovation is minor or if the innovation can be applied only to an unrepeatable incident. In addition, an incentive to keep an innovation secret will be strong if the person who creates the innovation cannot gain enough benefits by making it public. Thus an innovation will not be recorded if the costs of making the innovation public are higher than its expected benefits.

2.1.2.1 Minor innovations

A person who creates an innovation may be unaware of having created it if its contribution to improving productivity is minor. The person may also notice the increased productivity but not seek to identify the reason for the improvement because such an investigation may seem too costly. Finally, even if the mechanism of the innovation is noticed and specified, the person who created it may not record it if it is deemed to be minor. It is therefore clearly possible that minor innovations are not noticed, identified, or recorded.

Even if an innovation is unnoticed or unrecorded, it still can be used for production by the person who created it, whether consciously or unconsciously, while the person continues doing that job. Unnoticed innovations will vanish when that person quits doing the job. If innovations are recognized but unrecorded, it is possible that at least some of them could be handed down to other workers. Because these are isolated and "personal" occurrences within a small closed group, they would not constitute a piece of accumulated knowledge common to all human beings.

2.1.2.2 Innovations for unrepeatable incidents

Even if an innovation is not minor, it will not be recorded if it can be applied only to an unrepeatable situation. For example, a negotiation between a seller and a buyer will be basically unrepeatable. Similar negotiations may occur, but an identical one will not. There are also incidents that occur, for example, only on a specific machine installed at a particular location; these incidents are never reproduced at other machines installed at other locations. This type of isolated and non-reproducible incident can be interpreted as unrepeatable in a broad sense. In addition to these spatially unrepeatable incidents, each machine has unique characteristics even if it was designed to be exactly the same as other machines. There will not be sufficient incentive to record or widely disseminate an innovation that can be applied only to an unrepeatable situation or to a machine with unique characteristics.

2.1.2.3 Costs of disseminating and acquiring information

There will be a strong incentive to keep an innovation secret if the innovation spills over freely without compensation to the innovator. However, even if a patent could be taken out to obtain appropriate compensation, the incentive to keep the innovation secret will still be strong if the cost of dissemination exceeds expected revenues. If an innovation was created for a minor incident, benefits gained from the innovation will usually be smaller than the cost of dissemination, and the incentive to keep the innovation personal will be strong. The costs for making an innovation public can be classified into two types: dissemination costs and acquisition costs. Dissemination costs are the costs paid to make an innovation public and to disseminate it, for example, patent application fees, advertising costs, marketing costs, and similar expenditures. Acquisition costs are the costs paid to acquire and utilize an innovation that some other person created, for example, search costs, transportation costs, and training costs. Patent royalties are included in acquisition costs only if the market value of the innovation exceeds the royalty plus other acquisition costs. Generally, dissemination costs are likely to be larger than acquisition costs, excluding patent royalties.

Let δ indicate dissemination costs, η indicate acquisition costs, and π indicate the market value of an innovation. As argued above, in general $\delta > \eta$ if $\delta > \pi$; therefore innovations are categorized into the following three ranges depending on the relative value of π compared with those of δ and η (see Figure 1):

Range I: $\pi \ge \eta \ge \delta$ or $\pi \ge \delta \ge \eta$; patented accumulative innovations
Range II: $\delta > \pi \ge \eta$; uncompensated spillovers of accumulative innovations
Range III: $\delta > \eta > \pi$; non-accumulative innovations

If the market value of an innovation exceeds its dissemination and acquisition costs, the patent of the innovation will be sold and disseminated widely (Range I). If the market value of an innovation does not exceed its dissemination costs but exceeds its acquisition costs, the innovation will disseminate widely without compensation (i.e., uncompensated spillover; Range II). If the market value of an innovation does not exceed either cost, the innovation will not be disseminated and will be kept personal (i.e., non-accumulative innovation; Range III). Because it is highly likely that the number of minor innovations is far larger than the number of innovations that have high market values, the shape of innovation distribution slopes downward and to the right (Figure 1), and the distribution will have a long tail. This shape can be approximated simply by an exponential or Pareto distribution, but it is not necessary to assume a specific functional form of distribution. The important point is not the specific functional form of the distribution but its properties—if $\delta > \eta > \pi$, then non-accumulative innovations exist and there will be far more of them than of accumulative innovations.

2.2 The origin of non-accumulative innovation

It seems clear that non-accumulative innovations exist, but who creates them? Researchers can certainly create them, but so can ordinary workers. Usually, workers are implicitly assumed to do only what they are ordered to do and nothing else. Workers in this sense can be substituted for capital. If the cost of using capital is lower than that of using workers, capital inputs will be chosen rather than labor inputs. Generally, such robot-like workers have been assumed as the labor input in typical production functions. Of course, workers are not robots. They are human beings that are fundamentally different from machines—only humans can fix unexpected problems by creating innovations.

2.2.1 Unexpected problems require innovation

Actions taken to deal with expected incidents are determined by calculating the solutions to optimization problems that are built based on models constructed in advance. These calculations can be implemented by machines given a specific objective function, structural equations, parameter values, and necessary environmental information. However, this is not true if actions taken to deal with unexpected problems are required, because the models constructed in advance are guaranteed to be useful only for expected incidents, and they are not necessarily guaranteed to be applicable to unexpected incidents. When an unexpected problem occurs, workers in charge of the production first have to grasp the situation and then prioritize their actions. During these actions, the workers conduct two types of important intellectual activities: (1) discover unknown mechanisms that prevail in the surrounding environment and (2) invent new ways to manage the environment. That the problem is unexpected indicates that correct mechanisms for this particular situation are not known and need to be discovered, and on the basis of the newly discovered mechanisms, the structural equations and parameters in the model used for the plan of action should be revised. The revised model may indicate that there is no solution to resume efficient production, and new ways of managing the environment should be invented. Discovery and invention commonly involve the creation of something new, that is, innovation.

Machines deal with programmed tasks quite well, often much better than human beings. Conversely, machines cannot deal with non-programmed tasks. The performance of machines declines and often they stop working if unexpected problems occur because the machines do not have a program to deal with unexpected problems. When encountering unexpected problems, machines will immediately reach a dead end. They cannot solve unexpected problems by simply applying their pre-programmed optimization algorithms, and they cannot rewrite these algorithms to make them applicable to unexpected incidents. The revision or creation of models in the face of unexpected incidents can be implemented only by human beings.

2.2.2 Workers' innovations to fix unexpected minor problems

Is it either necessary or expected to utilize workers' innovations for production? If workers are assumed to be robot-like beings, their abilities to solve unexpected problems will not be considered as part of production. However, it would be irrational for firms not to utilize workers' innovative abilities if the firms know that workers possess these abilities. An ordinary worker's ability to solve unexpected problems may be lower than that of educated and trained researchers, but the abilities of the former should be utilized fully for a firm to be rational. If anything, the workers' abilities to fix unexpected problems appear indispensable in production processes because many minor but unforeseeable incidents actually occur. It would be quite inefficient if a team of specialized highly educated and trained employees dealt with all unexpected incidents, no matter how minor, and workers had to wait for the team to arrive at the locations where a minor unexpected incident happened. If, however, an unexpected but minor problem is fixed by a worker at the location where the problem occurred, production can proceed more efficiently and smoothly. The well-known "Kaizen" method in Japanese manufacturing companies may be a way to more completely exploit such opportunities (e.g., Lee et al., 1999). Besides innovations by suppliers, "user innovation" by consumers and end users has drawn attention recently (e.g., Baldwin et al., 2006). It is quite reasonable and rational for firms to fully exploit any opportunity to improve productivity whether its source is an innovation created by a researcher, ordinary worker, or user.

Finally, a worker's ability to fix unexpected problems may seem to be part of the set of the worker's learned skills or techniques, but that ability is fundamentally different from learned skills or techniques because learning skills and techniques and creating skills and techniques are completely different activities.

2.3 Imperfections make workers' innovations indispensable

Although it is rational for employers to fully exploit workers' innovations, in this section, I explain why workers' innovations are truly an indispensable element in production.

2.3.1 Imperfect accumulated innovations

The current state of accumulated innovations is far from perfect, and, moreover, it always will be. Human beings will never know everything about the universe. Although we may be able to fully utilize known information, we still face many unexpected problems because the knowledge and technology we currently possess is imperfect. If accumulated innovations were perfect, machines that embody them would always work well in any situation. However, the accumulated innovations are not perfect, and thus machines malfunction occasionally or face other unexpected incidents. As stated previously, it is very efficient if workers' innovations are utilized to fix these minor but unexpected troubles. Imperfection of accumulated innovations therefore necessitates workers' innovations.

2.3.2 Incomplete information caused by the division of labor

Labor input has the property of decreasing marginal product, which is usually explained by congestion or redundancy. However, this explanation is not necessarily convincing. The inefficiency caused by congestion or redundancy can be removed by division of labor. If labor is sufficiently divided, there will be no congestion or redundancy, and the labor input will not exhibit decreasing marginal product. This suggests that division of labor cannot remove all inefficiencies with regard to labor input. With division of labor, each worker experiences only a fraction of the whole production process. These divided and isolated workers can access only a fraction of information on the whole production process. It is also difficult for a worker to know information that many other workers at different production sites accessed. Because all of the labor inputs are correlated owing to division of labor, this feature of fragmented information is especially problematic when workers engage in intellectual activities. Correlation of the entire labor input indicates that all pieces of information on the whole production process need to be completely known to each worker to enable correct decision making. However, only a portion of the information on the whole production process is available to each worker; that is, each individual worker has incomplete information. When an unexpected problem occurs, workers with fragmented and incomplete information will make different, usually worse, decisions than those with complete information. As a result, overall productivity decreases.

For example, a CEO of a large company may know the overall plan of production but not the local and minor individual incidents that happen at each production site each day. In contrast, each worker at each production site may know little of the overall plan but a great deal about local and minor individual incidents that occur for each specific task each worker engages in at each production site. To be most efficient, even if many unexpected incidents happen, all of the workers and the CEO need to know all of the information on the entire process because all of the labor inputs are correlated owing to division of labor. However, it is nearly impossible for each worker to access all of the experiences of every other worker. Division of labor therefore leads to information fragmentation and obstructs any person from knowing all the information about the entire production process.

Each worker therefore must use incomplete information when encountering unexpected problems. Conjecturing the full detailed structure of the whole production process is an intellectual activity to discover unknown mechanisms. If a worker can discover more correct mechanisms even in the absence of complete information, the inefficiency is mitigated. Because inefficiency is inevitably generated by incomplete information resulting from division of labor, workers' innovations are inevitably needed to mitigate inefficiency. However, completely mitigating the inefficiency will be impossible, and decisions based on less information will deviate from those made with full information. Sometimes actions that are relatively less urgent or important will be given priority, and efficiency will decline. As the division of labor increases, workers are less able to correctly estimate the full structure of the whole production process and less able to correctly prioritize actions to solve unexpected problems.

Division of labor cannot simultaneously solve inefficiency caused by congestion or redundancy and that caused by fragmented and incomplete information. Although a greater division of labor removes the former, it generates the latter. Inefficiency resulting from congestion and redundancy is probably much more serious than that caused by information fragmentation, and labor is divided almost completely despite the fact that information fragmentation harms productivity.

2.3.3 Indispensable and economically important workers' innovation

Even if workers can innovate to fix unexpected minor troubles, the question remains whether these innovations are important economically. In general, most non-accumulative innovations are minor, which suggests that they may not be economically important. However, as discussed in Section 2.1, there will be far more minor innovations than major innovations. There are also usually far more ordinary workers than researchers and other highly trained or educated employees. In addition, the distributions of innovations for researchers and other highly trained employees and for ordinary workers are certainly different. Ordinary workers are likely to have a limited contribution to accumulative innovations (i.e., Ranges I and II in Figure 1) as compared to that of researchers and other highly trained employees, but the former will have a much larger contribution to non-accumulative innovations (Range III). As previously discussed, non-accumulative innovations are indispensable for production at each production site because of imperfect accumulative innovations and fragmented and incomplete information. Without worker-created non-accumulative innovations, the efficiency of production will decline considerably. This indispensability indicates that workers' innovations are economically important. The economic importance of workers' innovations is further examined in Section 4.

3 THE EXPERIENCE CURVE EFFECT

3.1 The experience curve effect and workers' innovations

Workers' innovations are indispensable, but how are they created? The experience curve effect gives a clue to this mechanism.

3.1.1 The theory of the experience curve effect

The experience curve effect states that the more often a task is performed, the lower the cost of doing it. Workers who perform repetitive tasks exhibit an improvement in performance as the task is repeated a number of times. The primary idea of the experience curve effect (the "learning curve effect" in earlier literature) dates back to Wright (1936), Hirsch (1952), Alchian (1963), and Rapping (1965). The importance of the learning curve effect was emphasized by Boston Consulting Group (BCG) in the late 1960s and early 1970s (e.g., BCG, 1972). The experience (or learning) curve effect has been applied in many fields, including business management, strategy, and organization studies (e.g., on airplanes, Wright, 1936; Asher, 1956; Alchian, 1963; Womer and Patterson, 1983; in shipbuilding, Searle and Goody, 1945; on machine tools, Hirsch, 1952; in metal products, Dudley, 1972; in nuclear power plants, Zimmerman, 1982; Joskow and Rozanski, 1979; in chemical products, Lieberman, 1984; Argote et al., 1990; in food services, Reis, 1991). More recently, it has also been applied to technology and policy analysis, particularly energy technologies (e.g., Yelle 1979; Dutton and Thomas, 1984; Hall and Howell, 1985; Lieberman, 1987; Argote and Epple, 1990; Criqui et al., 2000; McDonald and Schrattenholzer, 2001; van der Zwaan and Rablc, 2003, 2004; Miketa and Schrattenholzer, 2004; Papineau, 2006). An empirical problem of the experience curve effect is to distinguish dynamic learning effects from static economies of scale. After surveying empirical studies, Lieberman (1984) concluded that, in general, static scale economies are statistically significant but small in magnitude relative to learning-based economies (see also Preston and Keachie, 1964; Stobaugh and Townsend, 1975; Sultan, 1976; Hollander, 2003).

The experience curve effect is usually expressed by the following functional form:

$$C_N = C_1 N^{-(1-\alpha)} \tag{1}$$

where C_1 is the cost of the first unit of output of a task, C_N is the cost of the *n*th unit of output, *N* is the cumulative volume of output and interpreted as experience of a worker engaging in the task, and *α* is a constant parameter ($0 < \alpha < 1$). $\frac{C_{2N}}{C_N}$ and $1-\alpha$ are often called the progress ratio and learning rate, respectively. This log-linear functional form is most commonly used probably because of its simplicity and good fit to data. Empirical studies have shown that α is usually between 0.6 and 0.9. Studies by BCG in the 1970s showed that experience curve effects for various industries range from 10–25% cost reductions for every doubling of output (i.e., $0.58 \le \alpha \le 0.85$) (e.g., BCG, 1972). Dutton and Thomas (1984) present the distribution of progress ratios obtained from a sample of 108 manufacturing firms. The ratios mostly range from 0.7 to 0.9 (i.e., $0.48 \le \alpha \le 0.85$) and average 0.82 (i.e., $\alpha = 0.71$). OECD/IEA (2000) argues that industry-level progress ratios have a similar distribution as the firm-level ones shown in Dutton and Thomas (1984; see also, e.g., Hirsch, 1956; Womer and Patterson, 1983; Womer, 1984; Ayres and Martinas, 1992; Williams and Terzian, 1993).

The magnitude of *α* (or equivalently the progress ratio or learning rate) may be affected by various factors (e.g., Hirsch, 1956; Adler and Clark, 1991; Pisano et al., 2001; Argote et al., 2003; Sorenson, 2003; Wiersma, 2007). Nevertheless, the average *α* is usually observed to be almost 0.7 (i.e., a progress ratio of 0.8 and a learning rate of 0.3) as shown in BCG (1972), Dutton and Thomas (1984), and OECD/IEA (2000). It therefore seems reasonable to assume that *α* is 0.7 on average.

3.1.2 Information conveyed by experience

An important element that an experience conveys is information. By accumulating experiences of doing a task, a worker increases the amount of information known about the task and makes it more complete. In this sense, *N,* which indicates experience in equation (1), reflects the current amount of information a worker possesses about a task. Accumulated experiences will improve efficiency in implementing a task because the amount of information on the task increases. However, if other factors remain the same, the magnitude of improvement will diminish as N accumulates because the information on the task will approach saturation.

Let I be a set of the currently available maximum information on a task. Engaging in the task in a unit of period provides a subset of I to a worker. Engaging in more units of period (i.e., accumulating experience N) makes the information on the task the worker currently possesses ($\tilde{I}$) approach I (i.e., the difference between $\tilde{I}$ and I diminishes). A part of the subset of I the worker acquires in a unit of period will overlap the part of the subset of I the worker acquires in the next period. With more complete information, accordingly, efficiency will improve. Because $\tilde{I} \rightarrow I$ as $N \rightarrow \infty$, then the magnitude of improvement will asymptotically decrease as N increases. Nevertheless, this asymptotical decrease may not be a simple process. Some piece of information may be easily obtainable and some other piece may not be, and some portion of information may have a relatively large impact on efficiency and other portions have small effects. The functional form that describes the asymptotical decrease of the magnitude of improvement will depend on interaction between these effects. The log-linear functional form $C_N = C_1 N^{-(1-\alpha)}$ fits empirical data well and is simple, and thus it has been used mostly for the experience curve effect.

3.1.3 Extending the concept of the experience curve effect

Because the essence of experience is that it conveys information, the experience curve effect can be extended to a wide variety of tasks. The tasks need not be limited to a worker's repeated actions, that is, tasks whose experiences are divided by periods. For example, consider that a human activity can be divided into many experiences, each of which is obtained by different workers. Each experience conveys a subset of information, and a part of the subset overlaps with subsets regarding other experiences. The experience curve effect will be applicable to this kind of task by interpreting N as a subset all worker experiences, so a task in a period whose experiences are divided by workers will be also applicable to the experience curve effect in the same way that a task performed by a worker whose experiences are divided by periods is. Extending this logic suggests that tasks applied to the experience curve effect should not be limited to the ones whose experiences are divided only by periods or workers. As long as the task is a human intellectual activity and its experiences are divided by factors other than periods or workers, the task will also be applicable to the experience curve effect because it has the common nature that each divided experience conveys only a subset of all the information that affects the worker's intellectual activities. Nevertheless, the concept of the experience curve effect should not be expanded infinitely. It can be applied only to the tasks of workers, the performances of which differ depending on the amount of information the worker has.

3.2 The experience curve effect in the technology input

3.2.1 Dispersively embodied accumulative innovation in capital

To understand the mechanism for the creation of non-accumulative innovations, it is first necessary to examine how workers are in contact with capital inputs and the accumulative innovations embodied in them at each production site. Any single machine or tool cannot embody all the accumulated innovations in human history. Only a portion of accumulated innovations are embodied in each machine or capital input.

Furthermore, different types of machines or tools embody different kinds of accumulative innovations. This relationship between accumulative innovation and capital suggests that accumulative innovations are varied, divisible, and dispersed among capital inputs. If there are negative effects of congestion and redundancy in the embodiment of accumulative innovation in capital, this division of accumulative innovation improves productivity. Embodying more types of accumulative innovations in a machine or tool may make it a more general purpose machine or tool. In implementing a specific task, however, a general purpose machine or tool will be less useful and efficient than a specialized one because congestion and redundancy of the accumulative innovations will occur and reduce efficiency.

Suppose that there is only one economy in the world and that all workers in the economy are identical. Let $Y(A,K,L)$ be a production function where Y is production, A is technology (accumulated innovations), K is capital input, and L is labor input. A can be interpreted as indicating the total amount of technology and, at the same time, the total number of varieties of technology in the economy. Let also τA be the portion of A embodied on average in a unit of capital where τ is a positive parameter. To incorporate the idea that the division of A mitigates congestion and redundancy and improves efficiency for production, the following assumption is introduced:

$$\frac{\partial Y(\tau, A, K, L)}{\partial \tau} < 0 \quad , \tag{2}$$

which indicates that the smaller the value of τ (i.e., the smaller the magnitude of congestion and redundancy), the larger the production Y.

On the other hand, if τ is too small, there is the possibility that a piece of A is not embodied in any part of K. Without embodying any portion of A, K is no longer a machine or tool but merely a pile of useless materials. Avoiding this abnormal situation requires a condition that any K must embody at least some portion of A. If $\tau < \frac{1}{K}$, then the total amount of A used in the economy is $\tau AK < A$, and thus some portion of A is not embodied in any K, which indicates that the condition $\frac{1}{K} \leq \tau$ is necessary for avoiding the abnormal situation and that $\tau = \frac{1}{K}$ is the threshold value. As the rationale for the condition $\frac{1}{K} \leq \tau$ with the threshold value $\tau = \frac{1}{K}$, it is assumed here that the total differential $dY(\tau,A,K,L)$ with respect to A and τ is positive such that

$$dY(\tau,A,K,L) = \frac{\partial Y(\tau,A,K,L)}{\partial A} dA + \frac{\partial Y(\tau,A,K,L)}{\partial \tau} d\tau > 0 \tag{3}$$

for $\tau < \frac{1}{K}$, and thus

$$\frac{dY(\tau,A,K,L)}{d\tau} = \frac{\partial Y(\tau,A,K,L)}{\partial A}\frac{dA}{d\tau} + \frac{\partial Y(\tau,A,K,L)}{\partial \tau} > 0 \tag{4}$$

for $\tau < \frac{1}{K}$, which means that if τ is smaller than the threshold value $\frac{1}{K}$, then the reverse effect of the amount of A on production is much larger than the effect of the division of A on production. If $\frac{1}{K} \leq \tau$, then any portion of A is embodied in some K, and thereby $\frac{dA}{d\tau} = 0$ and $\frac{dY(\tau,A,K,L)}{d\tau} = \frac{\partial Y(\tau,A,K,L)}{\partial \tau} < 0$.

Combining the characteristics of τ shown in inequalities (2) and (4) indicates that the optimal value of τ is $\frac{1}{K}$. As a result of the rational behavior of firms, the optimal dispersion of accumulative innovation in capital is obtained when $\tau = \frac{1}{K}$, and thus the portion of A embodied on average in a unit of capital is always

$$\frac{A}{K}$$

in the economy. A worker faces $\frac{A}{K}$ units of accumulative innovations at any time when the worker uses a unit of capital.[1] Because A indicates the total number of varieties of technology as well as the total amount of technology, dispersively embodied A in K indicates that a worker faces $\frac{1}{K}$ of varieties of A when the worker uses a unit of capital.

3.2.2 Specialized or generalized machines or tools

Suppose that the amount of A is fixed; that is, no new variety of innovation is added. If K increases and A remains fixed, the proportion of A embodied in a unit of K becomes smaller because the proportion of A embodied in a unit of K is kept equal to $\frac{A}{K}$. A smaller $\frac{A}{K}$ means that machines or tools become more specialized because the purpose of a machine or tool embodying less A will be more limited. The types of machines or tools used will change even if A does not increase. If K increases in this case, machines and tools will become more specialized and vice versa. The variety and type of machines or tools, that is, how specialized or generalized they are, depend not only on A but also on K.

Note, however, that generalized does not necessarily mean advanced. On the contrary, general purpose machines or tools are more primitive, and conversely, special purpose ones are more advanced. To be general purpose, machines or tools must rely more on basic or core technologies, and many specialized functions will be downgraded.

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[1] In this paper, it is assumed that there is only one economy in the world. However, actually there are many smaller economies and a small economy may utilize only a small portion of A; i.e., the size of economy will matter to the optimal value of τ if there are many economies of various sizes. The problem of the size of economy as well as the problem of aggregation is discussed more in detail in Section 4.

3.2.3 Effective technology input

As argued in Section 3.1, the experience curve effect can be applied to a task as long as the task is an intellectual creative activity and the experiences can be divided by some factor. The experience curve effect is applicable to the activity of creating non-accumulative innovations to supplement imperfect accumulative innovations because (1) the activity is an intellectual creative activity and (2) the experiences can be divided by varieties of A in K a worker encounters. A worker encounters a portion of the accumulated innovations ($\frac{A}{K}$) when the worker uses a unit of capital. The portion of accumulated innovations conveys a subset of all the information on accumulated innovations and a part of the subset overlaps with those conveyed in other portions of accumulated innovations that other workers encounter.

A worker encounters a unique combination of varieties of accumulative innovations ($\frac{A}{K}$) per unit capital. Let N_A be a worker's average encounter frequency (i.e., the worker's experience) with each variety of accumulative innovations per unit capital in a period. As $\frac{A}{K}$ increases, the number of varieties per unit capital increases; thus, N_A will decrease because the probability of encountering each of the varieties in $\frac{A}{K}$ in a period decreases. The amount of $\frac{A}{K}$ therefore will be inversely proportional to a worker's experience on a variety per capital N_A such that

$$N_A = \beta_A \left(\frac{A}{K} \right)^{-1}$$

where β_A is a positive constant. Standardizing the worker's average encounter frequency β_A equal to unity, then

$$N_A = \left(\frac{A}{K} \right)^{-1} . \tag{5}$$

Let C_{A,N_A} be the amount of inefficiency resulting from imperfect technology (which is equivalent to imperfect accumulative innovations) embodied in capital when a worker utilizes a variety of accumulative innovations in $\frac{A}{K}$ in a period. C_{A,N_A} does indicates not the inefficiency initially generated by imperfect technology but the one remaining after being mitigated by workers' innovations. Costs increase proportionally to increases in inefficiency; thus, C_{A,N_A} also indicates costs. Conversely, C_{A,N_A}^{-1} can be interpreted as a productivity in supplementing imperfect technology by creating non-accumulative innovations when a worker utilizes a variety of accumulative innovations in $\frac{A}{K}$ in a period. The creation of non-accumulative innovations will increase as the frequency of a worker encountering a variety of accumulative innovations in $\frac{A}{K}$ increases (i.e., the productivity in supplementing imperfect technology by creating non-accumulative innovations will increase as the number of experiences increases). Hence, the inefficiency C_{A,N_A} will decrease as the encounter frequency increases. The experience curve effect indicates that inefficiency C_{A,N_A} declines (i.e., productivity C_{A,N_A}^{-1} increases) as a worker's average encounter frequency on a variety per unit capital (N_A) increases (i.e., $\frac{A}{K}$ becomes smaller) such that

$$C_{A,N_A} = C_{A,1} N_A^{-(1-\alpha)} \quad , \tag{6}$$

where $C_{A,1}$ is the inefficiency when $N_A = 1$. Note that α is the constant parameter ($0 < \alpha < 1$) used in equation (1).

In addition, the amount of technology input per unit capital will increase as C_{A,N_A}^{-1} increases (i.e., C_{A,N_A} decreases) because the inefficiency is mitigated by an increased amount of workers' innovations. Thus, the amount of technology input per unit capital when a worker uses a variety of accumulative innovations in $\frac{A}{K}$ will be directly proportional to C_{A,N_A}^{-1} (i.e., inversely proportional to C_{A,N_A}) such that

$$W_A \left(\frac{A}{K} \right)^{-1} = \frac{\gamma_A}{C_{A,N_A}} \quad , \tag{7}$$

where W_A is the amount of technology input per unit capital when a worker utilizes a unique combination of varieties of accumulative innovations in $\frac{A}{K}$, and γ_A is a positive constant (i.e., γ_A indicates the amount of technology input per unit capital when a worker utilizes a unique combination of varieties of accumulative innovations $\frac{A}{K}$ in a period when $C_{A,N_A} = 1$). Substituting equations (5) and (6) into equation (7) gives

$$W_A = \frac{\gamma_A}{C_{A,N_A}} \left(\frac{A}{K} \right) = \frac{\gamma_A}{C_{A,1} N_A^{-(1-\alpha)}} \left(\frac{A}{K} \right) = \frac{\gamma_A}{C_{A,1} \left(\frac{A}{K} \right)^{1-\alpha}} \left(\frac{A}{K} \right) = \frac{\gamma_A}{C_{A,1}} \left(\frac{A}{K} \right)^{\alpha} . \tag{8}$$

As discussed in Section 3.2.1, the amount of technology embodied in a unit capital is $\frac{A}{K}$. Because technology is imperfect, however, that level of technology input cannot be effectively realized. At the same time, the inefficiency resulting from the imperfections is mitigated by non-accumulative innovations created by ordinary workers even though it is not completely removed. Equation (8) indicates that the magnitude of mitigation depends on $\frac{A}{K}$, and that, with the mitigation, technology input per unit capital is effectively not equal to $\frac{A}{K}$ but directly proportionate to $W_A = \frac{\gamma_A}{C_{A,1}}\left(\frac{A}{K}\right)^{\alpha}$. By equation (8), therefore, the effective technology input per unit capital ($\widetilde{A}$) is

$$\widetilde{A} = \upsilon_A W_A = \omega_A \left(\frac{A}{K}\right)^{\alpha} \tag{9}$$

where υ_A and ω_A are positive constant parameters and $\omega_A = \left(\frac{\upsilon_A \gamma_A}{C_{A,1}}\right)$.

3.3 *The experience curve effect in the labor input*

The task of mitigating the inefficiency resulting from fragmented and incomplete information caused by the division of labor satisfies the condition for applying the experience curve effect (Section 3.1). As shown in Section 2.3, workers' innovations reduce this inefficiency. In addition, production processes are divided by workers as part of the division of labor. Each worker encounters only a portion of the whole production process, a portion of the process conveys only a portion of information on the whole production process, and the information overlaps partially with that on other processes that other workers encounter. Hence, the experience curve effect can be applied to this task. Because labor is divided fully at the global level, inefficiency mitigation activities are correlated at the global level.

Let N_L be the production processes a worker encounters (i.e., the experience of a worker); it indicates the proportion of all production processes in the economy (N), which is here normalized such that $N = 1$. A proportion of the production process conveys a subset of all the information on the production process, and a part of the subset overlaps with subsets of information on processes that other workers encounter. Remember, in this discussion, I am assuming that there is only one economy in the world and that all workers are identical. Thus, because the experience of a worker (N_L) is inversely proportionate to the number of workers, then

$$N_L = \frac{\beta_L}{L}$$

where L is the number of workers in the economy and β_L is a constant. $\beta_L (= N_L L)$ indicates the total of all production processes in the economy such that $\beta_L = N$. Because $N = 1$, then

$$N_L = \frac{1}{L}. \tag{10}$$

Let C_{L,N_L} be the magnitude of inefficiency in a worker's labor input caused by fragmented and incomplete information when each worker's experience is N_L. C_{L,N_L} indicates not the inefficiency initially generated by fragmented and incomplete information but the inefficiency that remains after mitigation by a worker's innovations. Costs will increase proportionally with increases in inefficiency, and thus C_{L,N_L} also indicates costs. C_{L,N_L}^{-1} can be interpreted as a productivity in a worker's labor input, which increases as the amount of mitigation by the worker's innovations increases.

C_{L,N_L} increases as the amount of individually available information (i.e., experience) increases. The increased amount of information enables a worker to discover more correct mechanisms of the production processes, and this discovery reduces the inefficiency in a worker's labor input. As mentioned previously, the experience curve effect can be applied to this inefficiency mitigation mechanism. The experience curve effect indicates that C_{L,N_L} declines as the experience of a worker (N_L) increases (i.e., the number of workers deceases) such that

$$C_{L,N_L} = C_{L,1} N_L^{-(1-\alpha)} \quad , \tag{11}$$

where $C_{L,1}$ is the inefficiency when $N_L = 1$ (i.e., $N_L = N$ and $L = 1$). Note again that α is the constant parameter ($0 < \alpha < 1$) used in equation (1).

In addition, because the amount of a worker's provision of labor input increases as productivity (C_{L,N_L}^{-1}) increases (i.e., C_{L,N_L} decreases), then the amount of a worker's provision of labor input ($\frac{W_L}{L}$) is directly proportional to C_{L,N_L}^{-1} (i.e., inversely proportional to C_{L,N_L}) such that

$$\frac{W_L}{L} = \frac{\gamma_L}{C_{L,N_L}} \quad , \tag{12}$$

where W_L is the total amount of workers' provision of labor input that is supplemented by worker's innovations to mitigate the inefficiency resulting from fragmented and incomplete information, and γ_L is a constant (i.e., γ_L indicates the output per worker in a period when $C_{L,N_L} = 1$). Substituting equations (10) and (11) into equation (12) gives

$$W_L = \frac{\gamma_L}{C_{L,N_L}} L = \frac{\gamma_L}{C_{L,1} N_L^{-(1-\alpha)}} L = \frac{\gamma_L}{C_{L,1} L^{1-\alpha}} L = \frac{\gamma_L}{C_{L,1}} L^{\alpha} \, . \tag{13}$$

The inefficiency caused by fragmented and incomplete information constrains the labor provision by workers. As division of labor is widened (i.e., as L increases), the labor provision by workers is more constrained. The inefficiency, however, is mitigated by innovations created by workers, but it cannot be completely removed by workers' innovations. Hence, the labor input that is effectively provided by workers is not simply proportional to L. Equation (13) indicates that, instead of L, the labor input effectively provided by workers is directly proportional to $W_L = \frac{\gamma_L}{C_{L,1}} L^{\alpha}$; thus, the effective labor input $\widetilde{L}$ is

$$\widetilde{L} = \upsilon_L W_L = \omega_L L^{\alpha} \quad , \tag{14}$$

where υ_L and ω_L are positive constant parameters and $\omega_L = \frac{\upsilon_L \gamma_L}{C_{L,1}}$.

3.4 The experience curve effect and the capital input

As with $\widetilde{A}$ and $\widetilde{L}$, an inefficiency with regard to the capital input K may exist, and this inefficiency may be solved by intellectual activities of workers. If such inefficiency exists, the effective capital input would not be equal to K. However, I was unable to find a factor that significantly necessitates a worker's intellectual activities to lessen inefficiencies in utilizing capital, in particular inefficiencies that result from imperfectness or incompleteness of information on capital. Therefore, I have assumed that capital input does not necessitate workers' innovations. However, capital input is constrained by another element that is basically irrelevant to workers' intellectual activities. It is impossible for each worker to use all capital inputs existing in the economy; each worker can access only a fraction of the total amount. This accessibility constraint sets bounds to the use of capital. Nevertheless, the accessibility is basically irrelevant in terms of worker innovation because accessibilities of workers in the world are not correlated with each other at the global level and thus it is not difficult for a worker to find a correct way to access capital inputs when an unexpected incident occurs. Therefore, information on accessibility is not incomplete, and it is enough for a worker to know only local information with regard to accessibility to capital. Therefore, there is little differentiation among workers in finding correct ways to access capital inputs, and as a consequence, there is little differentiation in the workers' experiences.

Machines or tools are not necessarily in constant operation during production; they are idle during some periods. A worker often uses various machines or tools in turn in a period, or equivalently several workers often use the same machine or tool in turn in a period. Let σK be the portion of K used by a worker on average where $\sigma(0 < \sigma \leq 1)$ is a positive parameter. Because the total sum of K used in the economy must not be smaller than K, $K \leq \sigma K L$, $\frac{1}{L} \leq \sigma$, and thereby $\frac{1}{L} \leq \sigma \leq 1$ for $1 \leq L$. It is highly likely that production increases if more K is used per worker, in which case

$$\frac{\partial Y(\sigma, A, K, L)}{\partial \sigma} > 0 \,. \tag{15}$$

Condition (15) and the constraint $\frac{1}{L} \leq \sigma \leq 1$ lead to a unique steady state value of σ such that $\sigma = 1$, which indicates that each worker uses all K existing in the economy.

Clearly, that is impossible—accessibility to capital is not limitless. Even if a worker wants to use *K* installed at a distant location, it is usually meaningless to do so because it is too costly. Thus, it is highly likely that there is a boundary of accessibility with regard to location. A worker can use only a small portion of *K* installed in the small area around the worker. That is, the value of the parameter σ has an upper bound such that

$$\frac{1}{L} \le \sigma \le \bar{\sigma} \quad , \tag{16}$$

where $\bar{\sigma}$ $\left(0 < \bar{\sigma} < 1\right)$ is a positive constant. With the upper bound $\bar{\sigma}$, by conditions (15) and (16), the optimal portion of *K* used by a worker on average ($\widetilde{K}$) for $1 \le L$ is

$$\widetilde{K} = \bar{\sigma} K \, . \tag{17}$$

The parameter $\bar{\sigma}$ represents a worker's accessibility limit to capital with regard to location.[2] The average value of $\bar{\sigma}$ in the economy will depend on the availability of physical transportation facilities. Location constraints, however, are not limited to physical transportation facilities. For example, law enforcement, regulations, the financial system, and other factors will also influence accessibility. The value of $\bar{\sigma}$ reflects the combined effects of all of these factors. The values of $\bar{\sigma}$ with regard to workers who are obliged to work at a designated location using fixed machines in a factory (e.g., workers in manufacturing industries) may be nearly identical. However, values for workers in other jobs (e.g., in service industries) will be heterogeneous depending on conditions. Even in manufacturing industries, workers engage in a variety of activities (e.g., negotiating with financial institutions or marketing), so the values of $\bar{\sigma}$ will also be heterogeneous in manufacturing industries.

Suppose that the density of capital per unit area is identical in the industrial area in the economy with an upper bound of $\bar{\sigma}$.[3] An increase of the total sum of *K* indicates an increase of the density of *K* in the industrial area; thus, the portion of *K* used by a worker also increases at the same rate as *K*. On the other hand, an increase of the total sum of *L* does not indicate any change of the density of *K* in the industrial area, and the portion of *K* used by a worker does not change.

3.5 Related theories

3.5.1 Learning-by-doing

The theory of learning-by-doing originated in Arrow (1962), who argues that productivity is improved by workers' regularly repeating the same type of action through practice, self-perfection, and minor innovation. Arrow-type growth models assume that productivity is proportionate to accumulated investments in capital or production, which represent the accumulated effects of workers' learning-by-doing (e.g., Sheshinski, 1967; Romer, 1986). If accumulated experiences obtained through

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[2] If there are many economies with various sizes, each economy's value of $\bar{\sigma}$ may be different. The effect of the size of economy on $\bar{\sigma}$ is discussed in Section 4.

[3] An industrial area is considered here to be an area that is appropriate for economic activities and excludes deserts, deep forests, mountains, and other inaccessible areas. This concept is important when we consider the size of economy, which will be examined in detail in Section 4.

learning-by-doing are proportionate not to accumulated innovations (A) but to accumulated past investments in capital or production and are heterogeneous across economies, current significant income differences across economies, which are difficult to explain by attributing the fundamental cause to A because A is homogenous among economies, can be explained. Arrow (1962) argues that different economies have different production functions because of heterogeneous amounts of accumulated learning-by-doing.

The concept of learning-by-doing is similar to the concept of the effective technology and labor inputs $\widetilde{A}$ and $\widetilde{L}$ in some aspects. They both focus on activities of ordinary workers. Indeed, some researchers base the foundation of the experience curve effect on the theory of learning-by-doing (e.g., Hall and Howell, 1985; Adler and Clark, 1991; Nemet, 2006). However, the concepts are different in the following important aspects.

- Learning-by-doing mostly consists of activities to learn already-uncovered knowledge, technologies, or ideas, but the creation of non-accumulative innovations by workers consists only of activities to create something new.
- Experiences obtained through learning-by-doing in Arrow-type growth models accumulate in the economy, but non-accumulative innovations created by workers do not accumulate.
- The amount of accumulated learning-by-doing in Arrow-type growth models is proportionate to accumulated investments in physical capital and production. The amount of non-accumulative innovations to supplement imperfect accumulated innovations is proportionate to accumulated innovations (A) and inversely proportionate to the physical capital input (K). The amount of non-accumulative innovations to mitigate the inefficiency resulting from fragmented and incomplete information is proportionate to the labor input (L).

3.5.2 Human capital

Human capital usually refers to a worker’s knowledge and skills that help increase productivity and performance at work and that are obtained by intentionally investing in education and training. The concept of human capital in the modern neoclassical economic literature dates back to Mincer (1958) and has been studied widely since Becker (1962, 1964). Human capital is similar to physical capital. Anyone can invest in it, and it is substitutable for physical capital and labor. Becker (1962) argues that investing in human capital means all activities that influence future real income through the embedding of resources in people. Investing in human capital takes the forms of formal schooling, on-the-job training, off-the-job training, medical treatment, and similar activities (e.g., Weisbroad, 1966; Lynch, 1991). Some researchers have argued that the currently observed international differences in investments and growth rates are closely related with human capital (e.g., Lucas, 1990; Barro, 1991; Benhabib and Spiegel, 1994).

The concept of human capital is similar to the concept of effective labor and technology inputs ($\widetilde{A}$ and $\widetilde{L}$) as well as learning-by-doing concepts in some aspects. These concepts commonly focus on the activities of ordinary workers. In Becker (1964), general and specific human capital inputs are distinguished because general human capital is useful not only with current workers but also with potential workers. Specific human capital in this sense is useful only with a current worker in a current job. Although researchers have argued that generating convincing examples of meaningful specific human capital is difficult (e.g., Lazear, 2003), specific human capital in the sense of Becker (1964) may consist partly of non-accumulative innovations. However, the concepts are different in the following fundamental aspects.

- A worker's human capital mostly consists of knowledge, technology, or ideas that have already been uncovered by other persons, but the creation of non-accumulative innovations by workers consists only of activities to create something new.
- Human capital obtained through education and training accumulates, but non-accumulative innovations do not.
- The amount of human capital is proportionate to variables that are unrelated to *A*, *K*, or *L* (e.g., periods of education or training). The amount of non-accumulative innovations to supplement imperfect accumulated innovations is proportionate to accumulated innovations (*A*) and inversely proportionate to physical capital input (*K*). The amount of non-accumulative innovations to mitigate the inefficiency resulting from fragmented and incomplete information is proportionate to the labor input (*L*).

These differences indicate that, as with learning-by-doing, the core concepts of human capital and effective technology and labor inputs are fundamentally different. The concept of effective labor and technology inputs focuses more specifically on creativity and non-accumulative innovations. The concept of human capital appears infinitely elastic, and its broad but ambiguous nature may confuse arguments. Many studies of human capital have narrowed the scope to education or training to avoid this ambiguity, although the concept of education still appears too broad for analyses of economic growth (e.g., Krueger and Lindahl, 2001).

4 PRODUCTION FUNCTION

4.1 Effective production function

Suppose that production requires some strictly positive minimum amounts of *A*, *K*, and *L*. In addition, suppose that *A*, *K*, and *L* each do not exhibit increasing marginal product; that is, $\frac{\partial^2 f(A,K,L)}{\partial A^2} \leq 0$, $\frac{\partial^2 f(A,K,L)}{\partial K^2} \leq 0$, and $\frac{\partial^2 f(A,K,L)}{\partial L^2} \leq 0$. If $\lim_{A \to \infty} \frac{\partial^2 f(A,K,L)}{\partial A^2} = 0$, $\lim_{K \to \infty} \frac{\partial^2 f(A,K,L)}{\partial K^2} = 0$, and $\lim_{L \to \infty} \frac{\partial^2 f(A,K,L)}{\partial L^2} = 0$, then for sufficiently large *A*, *K*, and *L*, the production function is approximated by the production function in which any of *A*, *K*, and *L* exhibits constant marginal product such that

$$Y = \psi_1 (A + \psi_2)(K + \psi_3)(L + \psi_4) + \psi_5 \quad , \tag{18}$$

where ψ_i (i = 1, 2, 3, 4, 5) are constants. Here, by the assumption that production requires some strictly positive minimum amounts of *A*, *K*, and *L*, then $f(0,K,L) = 0$,

$f(A,0,L)=0$, and $f(A,K,0)=0$. Among the approximated production functions (18), the production function that also satisfies this minimum requirement condition is

$$Y=\psi_1 AKL .$$

If ψ_1 is standardized such that $\psi_1=1$, then

$$Y=AKL . \tag{19}$$

Production function (19) appears intuitively understandable. Each of L workers uses K capital inputs per worker with A amount of technologies utilized in each K.[4] However, production function (19) cannot be realized as it is, because there are various constraints caused by various imperfections, as I argued in Section 3. The effective amounts of technology and labor inputs are not A and L but $\widetilde{A}$ and $\widetilde{L}$, and the portion of K usable for a worker on average is not K but $\widetilde{K}$. Hence, the approximated production function is effectively

$$Y=\widetilde{A}\widetilde{K}\widetilde{L} . \tag{20}$$

Here, by equations (9), (14), and (17),

$$\widetilde{A}\widetilde{K}\widetilde{L}=\omega_A\left(\frac{A}{K}\right)^{\alpha}\bar{\sigma}K\omega_L L^{\alpha}=\bar{\sigma}\omega_A\omega_L A^{\alpha}K^{1-\alpha}L^{\alpha} . \tag{21}$$

Rational firms utilize inputs fully so as to maximize Y, and by equations (20) and (21), the approximate effective production function (AEPF) can be represented as

$$Y=\bar{\sigma}\omega_A\omega_L A^{\alpha}K^{1-\alpha}L^{\alpha} . \tag{22}$$

4.2 The approximate effective production function

AEPF has the following properties, which have been widely assumed for production functions and are consistent with data across economies and time periods: a Cobb-Douglas functional form, a labor share of about 70%, and strict Harrod neutrality. The function therefore also has decreasing marginal products of labor, capital, and technology.

4.2.1 Cobb-Douglas functional form

The rationale and microfoundation of the Cobb-Douglas functional form have been long argued, but no consensus has been reached. For example, Jones (2005) argues that Cobb-Douglas production functions are induced if it is assumed that ideas are drawn from Pareto distributions. Growiec (2008), however, shows that Clayton-Pareto class of production functions that nest both the Cobb-Douglas functions and the CES are induced by assuming that each of the unit factor productivities is Pareto-distributed,

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[4] Remember that all workers are assumed to be identical.

dependence between these marginal distributions is captured by the Clayton copula, and that local production functions are CES. AEPF provides an alternative rationale and microfoundation of the Cobb-Douglas functional form. AEPF is the typical Cobb-Douglas production function, and the keys of its Cobb-Douglas functional form are workers' innovations and the experience curve effect.

4.2.2 A 70% labor share

The parameter α indicates the labor share in the distribution of income. Data in most economies show that labor share is about 70% (Table 1). No persuasive rationale has been presented on why the labor share is usually about 70%, but AEPF can offer one. In AEPF, the value of α is derived from the experience curve effect, and the average value of α has been shown to be about 70% in many empirical studies on the experience curve effect (e.g., Hirsch, 1956; Womer and Patterson, 1983; Dutton and Thomas, 1984; Womer, 1984; Ayres and Martinas, 1992: Williams and Terzian, 1993; OECD/IEA, 2000), which implies that workers' average rate of reducing inefficiencies is bounded. This boundary probably exists because newly added information decreases as the number of experiences increases and also because the marginal efficiency in a worker's analyzing, utilizing, and managing information (i.e., in creating innovations) decreases as the amount of information increases.

4.2.3 Strict Harrod neutrality and balanced growth

Because AEPF is a Cobb-Douglas production function, any of Harrod, Hicks, and Solow neutralities can be assumed as the type of technology change embodied in it. However, AEPF is Harrod neutral in the strict sense such that a unit of A is neither $A^{-\frac{\alpha}{1-\alpha}}$ (Solow neutral) nor $A^{-\alpha}$ (Hicks neutral) but A^{-1} because a unit of A is defined before the functional form of AEPF is induced using the experience curve effect. This strict Harrod neutrality is a necessary condition for a balanced growth path. In the balanced growth equilibrium, the capital intensity of the economy $\frac{K}{Y}$ is kept constant, and $\frac{Y}{L}$, $\frac{K}{L}$, and A grow at the same rate. Because AEPF is strictly Harrod neutral, it is possible for a growth model based on AEPF to achieve a balanced growth path.

At first glance, the essential factor behind the strict Harrod neutrality in AEPF appears to be that both $\widetilde{A}$ and $\widetilde{L}$ are subject to workers' intellectual activities and the experience curve effect. However, this view is somewhat superficial. In a deeper sense, there is a more essential factor. For strict Harrod neutrality to be achieved, it is necessary that both AEPF with constant L and AEPF with constant A be homogeneous of degree 1 with regard to (A and K) and (K and L), respectively. These conditions are satisfied in AEPF because $\widetilde{A}$ is $\omega_A\left(\frac{A}{K}\right)^{\alpha}$, and $\widetilde{A}$ therefore is not proportionate simply to A but to $\frac{A}{K}$. That is, strict Harrod neutrality requires various types of accumulative innovations in A to be dispersed in K, which means that A and K are closely related (like two sides of the same coin). Production (Y) increases at the same rate as A and K; thus, the capital intensity $\frac{Y}{K}$ is constant.

As shown in Section 3, the nature of dispersive accumulative innovations originates in the optimization of firms to minimize inefficiencies caused by congestion and redundancy of A (i.e., to maximize effects of the division of A). Because technology input is optimal when capital is as specialized as possible, then capital is actually as specialized as possible by the optimizing behaviors of firms, which implies that the very essence of the strict Harrod neutrality and the balanced growth path lies in the optimizing behaviors of rational firms.

4.3 The size of the economy and aggregation

Because AEPF has the Cobb-Douglas functional form, it is impossible to simply disaggregate it unless any disaggregated capital labor ratio $\frac{K}{L}$ has the same value. AEPF offers an explanation for this difficulty of disaggregation (or equivalently aggregation). The effective labor input $\widetilde{L}$ indicates that division of labor is a crucial factor for Cobb-Douglas production functions. Labor is divided at the global level, and even a division of labor in a small factory is a part of the global-level division of labor. Division of labor cannot be completed within a factory, but all divided labor inputs are correlated and not viable alone. Thereby, the global-level division of labor must be considered even if we construct a local production function. However, variables reflecting the global-level division of labor (e.g., the total number of workers in the world) are not included in local Cobb-Douglas production functions; that is, the effect of the global-level division of labor is ignored. The neglect of this effect matters more when local Cobb-Douglas production functions are aggregated to higher levels because the neglected correlations of labor inputs are not accounted for in the aggregation. Therefore, it is not possible to aggregate local Cobb-Douglas production functions by simply summing them up.

A similar problem may arise when a Cobb-Douglas production function is applied to multiple economies of different sizes. Large economies exhibit properties more similar to the global economy, and small economies exhibit properties that are less similar, which implies that a Cobb-Douglas production function cannot be applied equally to large and small economies. I have assumed that there is only one economy in the world, but if multiple economies are allowed, AEPF may have to incorporate the size of economy, for example, by including additional variables. However, the same AEPF can be applied to large and small economies without consideration of the size of economy because the size of an economy relates not only to $\widetilde{L}$ but also to $\widetilde{A}$ and $\widetilde{K}$.

Let $S(0 < S \leq 1)$ be the size of economy, and $S = 1$ indicates the entire global economy. Here, S is defined independently of endogenous variables Y and K but by an exogenous variable such as the spatial size of an economy's industrialized areas. Given identical population density in industrialized areas across economies, S is directly proportionate to a given L. If this spatial (population) size of economy is considered, $\widetilde{A}$, $\widetilde{K}$, and $\widetilde{L}$ need to be modified. Suppose an economy's Y, K, L, and S are Y_X, K_X, L_X, and S_X, respectively, and A is internationally common. First, the effective capital input $\bar{\sigma}K_X$ needs to be standardized by the spatial size parameter S_X. A worker's accessibility to capital does not depend simply on K_X anymore but on the spatial density of capital

$\frac{K_X}{S_X}$; thus, the capital inputs a worker can access are not $\bar{\sigma}K_X$ but $\bar{\sigma}\frac{K_X}{S_X}$. Hence, the effective capital input is not $\tilde{K}_X$ but $\frac{\tilde{K}_X}{S_X}$. Similarly, the effective technology input $\tilde{A}_X$ needs to be standardized by the spatial size of economy S_X. The dispersive nature of A implies that, although any variety of A is available to any economy, a small economy will not utilize all varieties in A but will specialize in a portion of the varieties in A. The amount of varieties an economy utilizes will depend on its size. Larger economies utilize more varieties in A, and smaller economies use fewer. With this conjecture, equation (5) ($N_A = \left(\frac{A}{K_X}\right)^{-1}$) needs to be adjusted by the size of economy S_X such that $N_A = \left(\frac{S_X A}{K_X}\right)^{-1}$; thus, by substituting $N_A = \left(\frac{S_X A}{K_X}\right)^{-1}$ into equation (8), the effective technology input is not $\tilde{A}_X$ but $S_X^{\alpha}\tilde{A}_X$. Finally, the effective labor input is no longer $\tilde{L}_X$. As was mentioned above, S is directly proportionate to L given an identical population density. A larger S (L) superficially indicates a wider division of labor and more fragmented and incomplete information and vice versa. Thereby, an economy with a larger S (L) superficially looks more strongly affected by the inefficiency of fragmented and incomplete information than a smaller economy even though labor inputs in both large and small economies are equally divided at the global level. To remove this distortion, N_L in equation (10) ($N_L = \frac{1}{L_X}$) must be artificially transformed to $N_L = \frac{S_X}{L_X}$ on the assumption that the size of the economy artificially becomes S_X^{-1} times as large (i.e., the same as the whole global economy). Hence, by substituting $N_L = \frac{S_X}{L_X}$ into equation (13), $\tilde{L}_X$ is modified to $\frac{\tilde{L}_X}{S_X^{\alpha}}$. Nevertheless, the actual labor input of the economy is S_X times smaller; thus, $\frac{\tilde{L}_X}{S_X^{\alpha}}$ must be multiplied by S_X to be used as the amount of labor input of the economy. The effective labor input is thereby not $\tilde{L}_X$ but $S_X^{1-\alpha}\tilde{L}_X$.

Substituting $S_X^{\alpha}\tilde{A}_X$, $\frac{\tilde{K}_X}{S_X}$, and $S_X^{1-\alpha}\tilde{L}_X$ for $\tilde{A}$, $\tilde{K}$, and $\tilde{L}$, respectively, in equation (20) as the effective technology, capital and labor inputs, AEPF adjusted for economy size is

$$Y_X = S_X^{\alpha}\tilde{A}_X \frac{\tilde{K}_X}{S_X} S_X^{1-\alpha}\tilde{L}_X = \tilde{A}_X\tilde{K}_X\tilde{L}_X \,. \qquad (23)$$

Equation (23) is exactly the same as equation (20). The spatial (population) size of the economy therefore does not matter, and AEPF can be applied equally to large and small economies. In addition, because equation (23) holds for any size economy, simple comparisons of the values of the parameters $\bar{\sigma}$, ω_A, and ω_L between large and small economies are possible, which enables us to evaluate the effects of heterogeneous parameter values on production. If estimated parameter values are different between two economies when the same AEPF is used, these different values should be interpreted not as a result of distortions caused by size but as reflecting intrinsically different economic structures between the two economies.

It must be noted, however, that aggregation is still impossible as is true with other Cobb-Douglas production functions unless $\frac{K}{L}$ is identical. Although S does not matter to the relation among Y, K, and L, aggregation demands an additional more restrictive constraint on the relation among Y, K, and L such that $Y_1 + Y_2 = f(K_1 + K_2, L_1 + L_2)$, where Y_i, K_i, and L_i indicate Y, K, and L for economy i. It is not the spatial size (S) but the size of Y that matters.

4.4 Incentives for workers to create innovations

The implicit assumption behind the parameters ω_A and ω_L is that workers create non-accumulative innovations to the greatest extent possible, which indicates that AEPF should be consistent with workers' incentives as well as firms' rational behaviors. AEPF indicates that higher ω_A and ω_L values yield higher production. Higher production benefits not only firms but also workers because the workers' share (α) is constant and higher production provides higher wages for workers. Hence, creating innovations is incentive compatible for workers, and AEPF indicates that rational firms encourage, or at least do not obstruct, workers' innovations, and workers are not reluctant but willing to innovate. Of course, the division of labor requires discipline, and the role of an individual worker in a production process is limited. Workers' activities deviating from their designated roles are usually prohibited. Nevertheless, within the given role of an individual worker, firms will fully encourage workers to innovate because it is incentive compatible both for firms and workers.

5 THE CONVERGENCE HYPOTHESIS

AEPF provides an alternative rationale, particularly a microfoundation of the Cobb-Douglas production function. However, providing it is not the most important aspect of AEPF. More importantly, AEPF provides important clues to answering questions about the convergence hypothesis.

5.1 International income differences and the convergence hypothesis

The convergence hypothesis states that per capita income, which is currently heterogeneous across economies, will converge at a unique identical level in the long run. The hypothesis argues that currently developing economies will eventually catch up with developed countries. Convergence is predicted by neo-classical Ramsey growth models. Given homogeneous preferences, any economy converges at a unique per capita production level even though the initial endowments of capital are heterogeneous. Many endogenous growth models have not supported the convergence hypothesis (e.g., Romer, 1986, 1987; Lucas, 1988). Endogenized knowledge accumulation significantly influences growth paths in these models, and if knowledge-acquisition processes (e.g., learning-by-doing or human capital accumulation) are heterogeneous among economies, there is no convergence of per capita GDP.

There are two main types of empirical studies on the convergence hypothesis: cross-country growth regressions (e.g., Abramovitz, 1986; Baumol, 1986; Barro, 1991; Barro and Sala-i-Martin, 1992; Mankiw et al., 1992; Jones, 1997) and time-series analyses (e.g., Bernard and Durlauf, 1995; Michelacci and Zaffaroni, 2000; Cheung and Garcia-Pascual, 2004). The conclusions of these studies are mixed and inconclusive. Roughly speaking, cross-sectional studies support the hypothesis, but time-series studies do not. The studies are inconclusive because the determinants of growth vary in the models, the data used often have deficiencies, and the groups of economies to which tests are applied also vary (e.g., Srinivasan, 1995; Bernard and Durlauf, 1996; Durlauf, 2003). Therefore, to date, determining whether the empirical evidence supports the hypothesis or not has been difficult. Prescott (1998) concludes that TFPs differ across economies and time for reasons other than differences in the publicly available stock of technical knowledge, and that a theory of TFP is needed to solve this problem.

5.2 Heterogeneous $\bar{\sigma}$, ω_A, and ω_L

5.2.1 Possibilities of heterogeneous $\bar{\sigma}$, ω_A, and ω_L

Convergence cannot be achieved if labor productivities among economies are heterogeneous in the long run. Heterogeneous labor productivities require elements other than A because accumulative innovation is common to any economy and naturally homogeneous. If elements other than A are heterogeneous, convergence is not necessarily guaranteed. AEPF contains several elements that influence productivity other than A, including α, $\bar{\sigma}$, ω_A, and ω_L. The parameter α is used in the conventional Cobb-Douglas production function, but the other three parameters are not. If at least one of these parameters is heterogeneous, the convergence hypothesis is not necessarily supported by AEPF.

As shown in Section 3, the average value of α is almost 0.7 in many empirical studies on experience curve effects, and labor's share in the distribution of income, which is theoretically equivalent to α, is also about 0.7 in many economies (Table 1). Because both of these two independent strands of empirical research indicate that α is about 0.7, the value of α at the macro level is probably similar in most economies and almost constant. Although there are some variations in observed values of α among economies and this heterogeneity may affect convergence, the magnitude of variation is smaller than the wide variance in per capita GDP. Thus, the heterogeneity of α does not appear to be the main cause for international income differences.

Each of the three newly introduced parameters ($\bar{\sigma}$, ω_A, and ω_L) will theoretically have significant effects on per capita production, the mechanism of which is easily understood by its functional form: $Y = \bar{\sigma}\omega_A\omega_L A^{\alpha}K^{1-\alpha}L^{\alpha}$. Nevertheless, whether these parameters take significantly heterogeneous values across workers and economies is not known. Although each of these parameters may take almost identical values in most economies, there is no *a priori* theoretical reason to assume that that is the case, and there are no existing empirical data indicating that the parameters are homogeneous.

If one of these parameters is heterogeneous, however, AEPF does not predict convergence, and there is no guarantee that an economy will reach a common steady state per capita income in the long run. Some developing economies may catch up with developed economies, but others may not, because of the heterogeneity. Whether the parameters in AEPF are heterogeneous, therefore, will provide an important clue to judge the validity of the convergence hypothesis.

5.2.2 A deeper theoretical explanation of the convergence hypothesis

AEPF is important in examining the convergence hypothesis because the structural parameters that can be heterogeneous are specified. Both theories of learning-by-doing and human capital explain the currently observed international income difference by heterogeneous accumulation of knowledge or human capital. They argue that accumulation is heterogeneous because of differences in, for example, the timing of industrialization or the amount of expenditure on education. These explanations do not include any mechanisms of how learning-by-doing and human capital explain international income differences. The explanations show only that knowledge or human capital accumulates heterogeneously. This feature has advantages and disadvantages. The income difference can be explained without presenting a deep structural mechanism, but these explanations are open to criticism because they are not built upon a firm theoretical foundation that explains a worker's experiences on a task even though the explanations emphasize the importance of the experiences.

AEPF, however, does not rely on heterogeneous accumulation to explain differences in international income. Instead, it is based on the heterogeneous structural parameters with regard to workers' experiences on tasks, and the mechanism is not a "black box." Instead, it is built upon the mechanism the experience curve effect describes. In this sense, AEPF certainly provides a deeper theoretical explanation of the convergence hypothesis than explanations that simply assume learning-by-doing or human capital and leave the mechanism unexplained. In addition, AEPF indicates that many factors may be related to the phenomenon of convergence and that convergence is a complicated phenomenon. Accumulation processes of human capital and learning-by-doing may impact convergence to some extent, but at the same time, the parameters $\bar{\sigma}$, ω_A, and ω_L (or equivalently $\bar{\sigma}, C_{A,1}, C_{L,1}$, γ_A, γ_L, υ_A, and υ_L) also may have impacts.

5.3 Heterogeneous $\bar{\sigma}$ and convergence

5.3.1 Accessibility and economic growth

The parameter $\bar{\sigma}$ indicates the accessibility of a worker to capital. If accessibility improves, both the value of $\bar{\sigma}$ and production increase. Improving accessibility broadens production opportunities. As argued in Section 3, accessibility consists not only of physical transportation facilities but also of law enforcement, regulation, the financial system, and other factors. Establishing high-grade institutions (e.g., government) and a financial sector and investing in physical capital (e.g., on transportation) are equally important for accessibility and economic growth. Nevertheless, emphasizing good institutions and the financial sector as driving forces of economic growth is not a new idea. Establishing them has been long regarded as an important element for promoting economic growth (e.g., Temple, 2000).

5.3.1.1 Institutions and growth

It has been argued that good institutions enhance economic growth (e.g., Knack and Keefer, 1995; Mauro, 1995; Hall and Jones, 1999; Acemoglu et al., 2001, 2002; Easterly and Levine, 2003; Dollar and Kraay, 2003; Rodrik et al., 2004). North (1981) define an institution as a set of rules, compliance procedures, and moral and ethical behavioral norms designed to constrain the behavior of individuals in the interests of maximizing the wealth or utility of principals. Acemoglu et al. (2005) conclude that differences in economic institutions are empirically and theoretically the fundamental cause of differences in economic development. Nevertheless, some economists argue the reverse causation from growth to institutional improvement (e.g., Barro, 1999) or that institutional improvement has a smaller impact on growth than human capital (Glaeser et al., 2004).

Acemoglu et al. (2005) sum up the rationale of the causation from institutions to growth by arguing that institutions shape the incentives of key economic actors in society. In particular, institutions influence investments in physical and human capital and technology and influence the organization of production. They also influence not only the size of the aggregate pie but how this pie is divided among different groups and individuals (i.e., the distribution of wealth and of physical or human capital). Some aspects of institutions are certainly closely related to accessibility because appropriate enforcement of laws and uncomplicated regulations enhance accessibility, which is in line with better organization of production and distribution of resources. Therefore, if institutions in an economy are well organized and function properly, a high degree of accessibility will be obtained, which drives growth. In this sense, the argument for institution-driven growth is consistent with AEPF.

5.3.1.2 Financial development and growth

Since the early 20th century, it has been argued that financial development leads to long-run economic growth (e.g., Schumpeter, 1939), and in the 1990s, empirical studies on the relation between financial development and economic growth were revitalized (e.g., King and Levine, 1993a, b; Levine and Zervos, 1996; Demetriades and Hussein, 1996; Levine, 1997; Luintel and Khan, 1999; Beck et al., 2000; Levine et al., 2000; Beck and Levine, 2002; Wachtel, 2003; Abu-Bader and Abu-Qarn, 2008). A positive correlation between financial development and growth has been observed in most empirical studies, but the direction of causality has not been conclusively identified. The mechanisms likely work in both causality directions, that is, from financial development to growth and from growth to financial development.

Proposed rationales of the finance growth nexus include the following: (1) financial development reduces friction in markets, especially in capital accumulation and technological innovation (e.g., Levine, 1997), and (2) financial systems play a critical role in allocation of resources, which is crucial for innovative activities (e.g., Schumpeter, 1912/1934; Shaw, 1973). Because the financial sector is a type of institution, a similar institutional rationale can be applied to it. As a financial sector develops, accessibility will improve as a result of lower costs and improved convenience of financial services with reduced friction and better allocation of resources, and workers can access a wider range of capital inputs more easily. In this sense, the proposition that financial development causes long-run economic growth is consistent with AEPF.

5.3.2 Accessibility and convergence

Institutions and financial sectors theoretically can be heterogeneous across economies. As argued in Section 3, the value of $\bar{\sigma}$ for service industries will be heterogeneous. The heterogeneity of $\bar{\sigma}$ for manufacturing industries may be smaller than that for service industries, but the heterogeneity of $\bar{\sigma}$ for manufacturing industries will not be negligible. A smaller value of $\bar{\sigma}$ for service industries indicates lower efficiency of overall economic activities and implies smaller investments and negative impacts on manufacturing industries. Hence, a high value of heterogeneity in $\bar{\sigma}$ will have a significant impact on the heterogeneity of the overall production process. The parameter $\bar{\sigma}$ therefore suggests not convergence but rather indefinite income differences. It also suggests that improving accessibility (i.e., establishing good institutions and a financial system as well as investing in physical transportation facilities) is an important policy issue.

5.4 Heterogeneous ω_A and ω_L and convergence

5.4.1 Effects of heterogeneous ω_A and ω_L

The parameters ω_A and ω_L originate in a worker's intellectual activity. If ω_A and ω_L are heterogeneous, the worker's intellectual activity will have an impact on convergence. If ω_A or ω_L values are heterogeneous across economies, production levels will also be heterogeneous even if accumulative innovations *A* are not, which implies an important and negative assessment of the convergence hypothesis. Suppose that there are two economies (economy 1 and 2) that have the same value of $\bar{\sigma}$ and the same preferences, but the value of $\omega_A\omega_L$ in economy 1 is v (> 1) times that of economy 2.[5] In Ramsey-type growth models, the rate of time preference (θ) is equal to the real rate of interest (r) at steady state, and r is always equal to marginal productivity with respect to capital. Hence,

$$\theta = r = v\left(\frac{A}{k_1}\right)^{-\alpha} = \left(\frac{A}{k_2}\right)^{-\alpha} \tag{24}$$

at steady state; thus,

$$\frac{A}{k_1} < \frac{A}{k_2} \quad , \tag{25}$$

where k_i is $k = \frac{K}{L}$ of economy i (i = 1 or 2). The per capita production of economy 2, which has the smaller value of $\omega_A\omega_L$, is lower than that of economy 1 at steady state because $k_2 < k_1$ by equation (25), and therefore heterogeneous ω_A and ω_L make per capita production heterogeneous. The parameters ω_A and ω_L (or equivalently $C_{A,1}, C_{L,1}$, γ_A, γ_L, υ_A, and υ_L) directly relate to the creative activities of ordinary workers, which indicates that the heterogeneous intellectual, particularly creative, activities of ordinary

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[5] Accumulative innovation *A* is the same in both economies.

workers can be a source of wide differences in per capita GDP. The more ordinary workers fix minor but unexpected problems, the higher overall productivity is, and a higher per capita GDP is possible. To reduce the international income difference, it is not sufficient for developing economies to merely import existing technologies, they must also enhance the creative activities of ordinary workers.

Equation (25) also indicates that economy 2, which has a smaller value of $\omega_A\omega_L$, will use more general purpose machines or tools than economy 1. Even if more advanced machines are available, less advanced (more general purpose) machines are appropriate when the value of $\omega_A\omega_L$ is relatively small. This outcome is forced not by some type of friction but as a natural consequence of optimality. Indeed, empirical studies have shown that the effect of technology transfer to developing economies is more positive in low-tech sectors than in high-tech sectors (e.g., Haddad and Harrison, 1993). Keller (1996), Borensztein et al. (1998), and others argue that an economy's absorptive capacity is crucial for successful technology transfer. Although their arguments may be indirect, they lend support to the idea of heterogeneous values for ω_A and ω_L.

5.4.2 An unknown additional fundamental factor input

I have shown that heterogeneous values of ω_A and ω_L will lead to income differences, but the question of whether ω_A and ω_L (or equivalently $C_{A,1}, C_{L,1}$, γ_A, γ_L, υ_A, and υ_L) are significantly heterogeneous across workers and economies remains open. As shown in Section 3, $C_{A,1}$ and $C_{L,1}$ indicate inefficiencies. $C_{A,1}^{-1}$ and $C_{L,1}^{-1}$ are productivities, suggesting that they are a kind of knowledge, technology, or idea in a similar sense to TFP; that is, they are included in accumulated innovations A. If they really are knowledge, technology, or ideas, they can spill over as accumulated innovations and are common to any worker and economy, which indicates that $C_{A,1}$ and $C_{L,1}$ cannot be heterogeneous unless some frictions or irrationality are assumed. However, $C_{A,1}^{-1}$ and $C_{L,1}^{-1}$ cannot be accumulated knowledge, technology, or ideas and can be heterogeneous for the following reason.

$C_{A,1}^{-1}$ and $C_{L,1}^{-1}$ are productivities in that they represent workers' mitigation of imperfections through innovation, and innovation is a human intellectual activity. As I have emphasized, human intellectual activity differentiates human beings from robots or other machines. A machine can substitute for a human only if the task does not require innovation. This fundamental difference indicates that, besides A, K and L, an additional factor input is required to create innovations, and only humans can provide it. Because the additional factor input must be provided by human beings, it is fundamentally different from the accumulated innovations (A) that can be provided by machines. Hence, $C_{A,1}^{-1}$ and $C_{L,1}^{-1}$ do not represent accumulated knowledge at all.

An important feature of this additional fundamental factor input is that it will not necessarily be common across workers and economies, because it has not been recorded. Because it is not recorded, the additional fundamental factor input cannot spill over, which implies that it is intrinsically not transferable. Because it is not transferable, the additional fundamental factor input for creating innovations is isolated within each individual worker. It can therefore be heterogeneous, and the parameters ω_A and ω_L can also be heterogeneous across workers and economies.

5.4.3 Creative activities of ordinary workers

Which elements in the environment surrounding ordinary workers make ω_A and ω_L heterogeneous and how can their values be increased? In particular, it is important from a policy perspective to increase the values of ω_A and ω_L in economies in which they are relatively low. It is important to emphasize that, in exploring policies to improve the working environment, ordinary workers create most non-accumulative innovations and determine the values of ω_A and ω_L by creating innovations in their day-to-day work. To my knowledge, the mechanism of ordinary workers' intellectual activities determining ω_A and ω_L (equivalently $C_{A,1}, C_{L,1}$, γ_A, γ_L, υ_A, and υ_L) is unknown. Many factors may influence this mechanism, for example, education, training, tradition, political and social environments, preferences, and the nature of the human brain. Studying this mechanism may well be beyond the scope of economics and may involve fields such as neurobiology, psychology, and pedagogy.

6 CONCLUDING REMARKS

Workers are human and thereby can create innovations even if those innovations are usually minor. Rational firms must fully exploit the opportunities that workers' innovations offer. In particular, innovations are necessary to supplement imperfect accumulated innovations and inefficiency in information sharing caused by the division of labor. The full nature of workers' innovation cannot be captured by the conventional concept of either labor input or technology input. To understand it properly, how innovations are created must be understood. The experience curve effect describes a mechanism of ordinary workers' intellectual activities to create innovations. Incorporating workers' innovations and the experience curve effect, I introduced a production function that has a Cobb-Douglas functional form, a labor share of about 70%, and strict Harrod neutrality, all of which are consistent with the important assumptions adopted in production functions that have been used in many economic analyses, but this function presents an alternative rationale for these properties. In particular, it presents a microfoundation of the Cobb-Douglas production function. This consistency indicates that worker's innovations are indispensable and economically important.

The most important nature of AEPF, however, is that it provides an important clue to judge the validity of the convergence hypothesis in growth economics. AEPF presents a theory of TFP, and this theory indicates that, if institutions have heterogeneous properties or if the structural parameter of workers' innovations is heterogeneous across economies, differences in GDP per capita across economies are possible. This prediction suggests that the quality of institutions and the productivity of workers' innovations are essential factors in the currently observed wide differences in GDP per capita. This result suggests that the mechanism of how ordinary workers create innovations should be more intensively studied.

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Figure 1 ***The distribution of innovation***

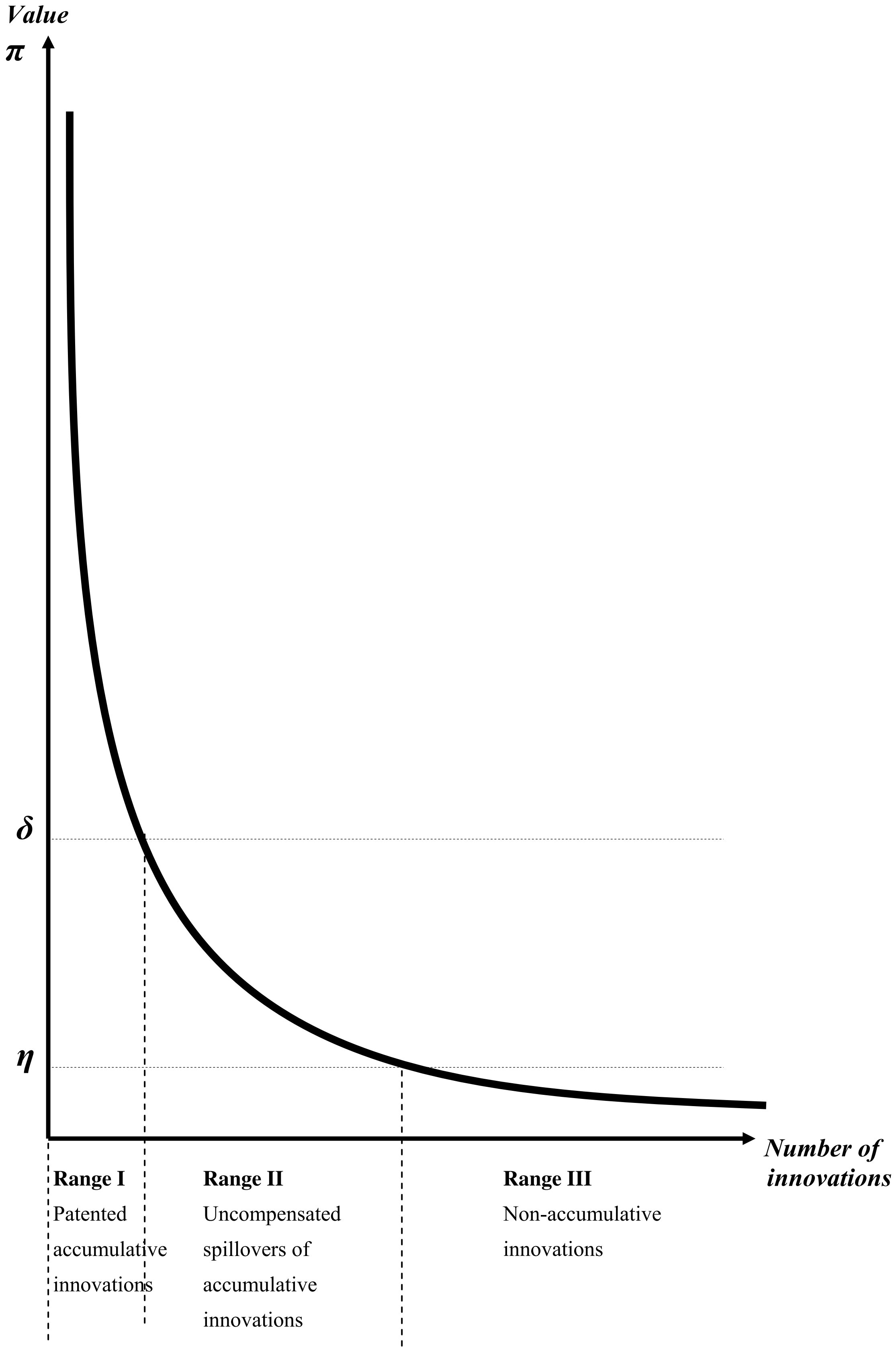

Table 1. Labor Income Share

	1990	**1995**	**2000**	**2005**	**2006**	**2007**
(OECD members)						
Australia	0.661	0.651	0.638	0.605	0.598	–––
Austria	0.82	0.759	0.729	0.692	0.685	0.677
Belgium	0.681	0.694	0.688	0.674	0.67	0.672
Canada	0.655	0.63	0.613	–––	–––	–––
Czech Republic	–––	0.552	0.56	0.587	0.585	0.582
Denmark	0.698	0.666	0.671	0.685	0.688	0.703
Finland	0.729	0.658	0.617	0.64	0.631	0.616
France	0.705	0.688	0.675	0.671	0.67	–––
Germany	0.694	0.698	0.7	0.666	0.656	0.65
Greece	0.643	0.624	0.633	0.603	0.59	–––
Hungary	–––	0.669	0.609	0.639	0.618	0.616
Iceland	0.543	0.567	0.657	0.69	–––	–––
Ireland	0.641	0.633	0.548	0.554	0.554	0.561
Italy	0.767	0.703	0.662	0.67	0.677	0.672
Japan	0.631	0.636	0.617	0.576	0.577	–––
Korea	0.835	0.838	0.769	0.767	0.77	0.767
Luxembourg	0.608	0.567	0.559	0.549	0.518	0.529
Mexico	0.428	0.433	0.444	0.426	0.405	–––
Netherlands	0.692	0.692	0.685	0.671	0.668	0.67
New Zealand	0.511	0.489	0.468	–––	–––	–––
Norway	0.633	0.616	0.545	0.517	0.506	0.53
Poland	–––	0.599	0.613	0.567	0.561	0.562
Portugal	0.685	0.697	0.72	0.725	0.718	–––
Slovak Republic	–––	0.525	0.525	0.506	0.488	–––
Spain	0.672	0.678	0.667	0.632	0.63	0.624
Sweden	0.726	0.655	0.679	0.675	0.66	0.667
Switzerland	0.629	0.646	0.642	0.659	0.66	–––
Turkey	0.557	0.423	0.48	0.419	0.4	–––
United Kingdom	0.706	0.677	0.693	0.686	0.686	0.667
United States	0.684	0.674	0.686	0.659	0.656	–––
Euro area	0.681	0.667	0.648	0.632	0.628	0.624
(Non-OECD members)						
Bulgaria	–––	–––	0.527	0.553	0.537	0.566
Cyprus	–––	0.626	0.6	0.642	0.629	0.63
Estonia	–––	0.654	0.573	0.55	0.562	0.618
Latvia	–––	0.587	0.543	0.536	0.565	0.624
Lithuania	–––	0.533	0.552	0.542	0.56	0.578
Romania	–––	–––	0.688	0.635	0.612	–––
Slovenia	–––	0.82	0.726	0.704	0.697	0.687

Source: OECD Stat Extracts (http://webnet.oecd.org/wbos/index.aspx)