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Evolutionary Dynamics of the Market Equilibrium with Division of Labor*

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Abstract: Recently, a growing literature, known as the new classical economics, attempts to resurrect the classical economic thoughts on division of labor within an analytical framework inherited from neoclassical economics. The paper inspects the feasibility of this approach and finds that the current analytical framework of the new classical economics is not able to spell out how individuals' decisions on specialization are coordinated and how division of labor is realized in a large and decentralized economy. Evolutionary dynamics are then introduced into the existing models. Using a simple economy for example, the paper shows that the equilibrium network of division of labor predicted by the new classical economics is supported by evolutionary stability and can be realized by the outcome of evolutionary processes, such as Replicator Dynamics. Mutation is important in the realization of division of labor since it provides an approach for the economy to escape from an initial state of autarky. The study implies that the inherent evolutionary process of the market constructs an "invisible hand", which can spontaneously coordinate self-interested individuals' decentralized decisions on specialization to discover an efficient order of division of labor in a large economy.

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1. Introduction

Since Marshall (1890), economists have got used to formulating the function of the market in resource allocation within a narrow scope that regards the network of division of labor as given[1]. However, because of the following reasons, this narrow perspective is not desirable. Firstly, Marshall's framework is based on the dichotomy between pure consumers and pure producers. This assumption implies that there is an ad hoc market structure and individuals are not allowed to choose what to sell and buy but only need to decide how much to sell and buy[2] (Yang and Ng, 1993, p.3). This is apparently unrealistic. Secondly, the idea that division of labor is the mainspring of economic progress and the idea that a competitive market can spontaneously coordinate individuals' decentralized decisions to realize an efficient "order" for the economy are two cornerstones of classical economics (Adam Smith, 1776). To formalize the two ideas within a united theoretical framework, it is necessary to construct models to convince people that a competitive market is not only able to coordinate individuals' decisions on how much to sell and buy to obtain an efficient resource allocation under a given network of division of labor, but also able to coordinate individuals' decisions on what to sell and buy to obtain an efficient network of division of labor.

Among the critics[3] against Marshall's narrow framework, a growing literature, known as new classical economics, is engaged in modeling the determination of division of labor in a competitive economy[4]. This literature has two major features. First, it regards all aspects of division of labor as endogenous outcomes of the market and hence it is more "classical" than other literatures. Second, by simply relaxing the dichotomy between pure consumers and pure producers, it tries to endogenize

[1] In the analytical framework of Marshall (1890), the number of goods traded on the market is given and there is a dichotomy between pure consumers and firms. These features make the neoclassical framework incapable of endogenizing division of labor. This framework was followed by economists.

[2] The decision on what to sell and buy is equivalent to an individual's choice of specialization or profession.

[3] Examples are Young (1928), Stigler (1976), Rosen (1977, 1983), Becker (1981), Becker and Murphy (1991), Baumgardner, (1988), Kim (1989), Locay (1990). See Yang and Ng (1998) for a more complete survey.

[4] Representatives in this literature include Yang and Borland (1991), Yang and Shi (1992), Yang and Ng（1993）, Yang and Ng (1993) , Yang (2001, 2003), Sun, Yang and Yao (2004), and Sun, Yang and Zhou (2004) (see Cheng and Yang 2004 for a more complete survey).

division of labor within the general-equilibrium analytical framework developed by the neoclassical economists [5] (it is briefly called “the neoclassical model” in this paper). Because of these reasons, they regard their theory as the “resurrection of classical economic spirit in a neoclassical body” (Yang and Ng, 1993, p.38). Recently, the framework developed by the new classical economics has attracted a lot of attention from relevant researchers and been applied to various fields of economic studies[6]. As a *Journal of Economic Literature* reviewer put it: this framework provides “a refreshing new approach to microeconomics, one that has the potential to address many issues that have long resisted formal treatments” (Smythe, 1994).

The new classical framework has made significant contributions to the study of division of labor; however, as a developing theory, there are some defects existing in its models. One of them is the absence of a rigorous explanation that can explicitly spell out how an efficient network of division of labor eventuates from decentralized decisions of individuals as a “spontaneous order” (Hayek, 1973) in a large, competitive economy (see Section 2 for detailed analysis). Ng (2004, p.243-6) is the first economist who takes this problem seriously. In his book he noticed that two types of coordination problems may exist in the current framework of the new classical economics. First, “the required coordination is over and above that provided by the price system” in the determination of equilibrium of division of labor in an economy with a fixed set of consumption goods. Second, a much more complex coordination mechanism (comparing with the simple price system and the coordination under the fixed number of goods) is needed in “the case of introduction of a new good”. In the paper, I will concentrate on the first coordination problem.

Given that the existing literature has not provided any formal model of the

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[5] In this model, the state of the economic system at any point of time is formulated as the solution of a system of simultaneous equations representing the demand for goods by consumers, the supply of goods by producers, and the equilibrium condition that supply equal demand on every market (Arrow and Debreu, 1954). This model was established by neoclassical economists such as Marshall (1890) and Walras (1900), and was followed and developed by mainstream economists. Currently, it is the main body of most textbooks of microeconomics.

[6] For a complete survey of applications of new classical economics, see Cheng and Yang (2004).

coordination problem of division of labor, this paper attempts to fill up the vacant. By re-formulating the new classical model to take into account of the evolutionary nature of the real economy, the paper shows that an efficient network of division of labor can be realized by the outcome of the evolutionary process associated with individuals' decision making and interaction. This gives a rigorous explanation to the coordination of division of labor in the real world. Whilst the theoretical foundation of new classical economics is based on inframarginal analysis (See Yang 2001, 2004 for a complete introduction of inframarginal analysis), this paper relies on evolutionary game theory. In this sense, it also provides a new approach and a dynamic framework to explore economic issues related with division of labor. Although there are substantial differences between my approach and the inframarginal analysis, however, the main purpose of the paper is not to diminish the significance of the new classical economics, rather, is to make it better and to strengthen its capability of explaining economic phenomena.

The rest of the paper is organized as following. In Section 2, the new classical economic models on division of labor are analyzed. We can see that these models are not able to give a satisfactory explanation to the determination of division of labor in the real world. In Section 3 and 4, I will introduce evolutionary factors into the formalization and consider the determination of division of labor within an environment of evolutionary games. A static analysis will be first presented in Section 3 and then the dynamical analysis in Section 4. In both sections, we will see that the Walrasian equilibrium of division of labor can be realized by the outcome of evolution. The analysis shows that the three factors of evolution – inheritance, selection and mutation – construct an "invisible hand" that can discover an efficient allocation of population over different professions to fully utilize positive network effects of division of labor net of transaction costs.

To simplify the analysis, throughout the paper I will consider a specific economy

$E = (I, u, x, y, L, a, k)$[7]. In this economy, there is an infinite set of *ex ante* identical consumer-producers I, two consumer goods x and y, and one resource L. Each individual has the same preference that can be represented by the utility function

$$u(x, y, x^d, y^d) = (x + kx^d)(y + ky^d) \tag{1}$$

where x and y are the self-provided quantities of the two consumer goods respectively, x^d and y^d are the quantities of the goods purchased from others, $k \in [0,1]$ represent the transaction efficiencies of the two goods. Each individual also has the same system of production functions and the same recourse constraint as following

$$x + x^s = l_x^a; \quad y + y^s = l_y^a \tag{2}$$

$$l_x + l_y = 1 \tag{3}$$

where x^s and y^s are the quantities of the goods sold to others; l_x and l_y are the amounts of the resource (labor) input in producing the two goods respectively. The total available quantity of resource for each individual is L, which is normalized as one unit. $a > 1$ indexes the degree of the economy of specialization. Although the analysis is based on a simple example, the main conclusions attained in this paper may also apply to general cases.

[7] It is exactly the same as the one adopted by Yang and Ng (1993, Chapter 2).

2. Comments on the new classical models

In the existing literature of the new classical economics, two different models have been developed to endogenize division of labor within a large, decentralized economy. The first model is a generalization of the neoclassical model of resource allocation; the second is an application of Nash's bargaining model. In this paper, they are called *Walrasian model* and *bargaining model*, respectively. These two models, especially the first one, construct the theoretical foundation of the new classical economics and have been applied to a broad range of economic issues (See Yang and Ng, 1998). However, in my opinion, neither of them has well spelt out how division of labor is coordinated and realized in the real world.

In the Walrasian model, individuals are assumed to make decisions independently. Each individual needs to allocate his resource – one unit of labor – between the productions of two consumption goods. He can choose autarky by producing both two goods or choose specialization by producing just one good and trading with other people to get another good. The market where individuals exchange goods is assumed to be a Walrasian regime. In the market, each individual is a price taker who treats the price as parametric. The outcome of the economy, named *Walrasian equilibrium* (Yang and Ng, 1993) or *competitive equilibrium* (Sun, Yang and Yao, 2004), is defined as a set of prices and a set of individuals' choices, that (C1) maximize each individual's utility, (C2) clear all markets, and (C3) equalize all individuals' utilities (from the assumption of identical individuals). Sun, Yang and Yao (2004) has proved the existence and the Pareto efficiency of the Walrasian equilibrium for a general family of cases, including economy E. For a specified model, we may use properties (C1)-(C3) to solve the equilibrium.

Apply the assumption of Walrasian regime to economy E. If the market exists, i.e., the total demand and total supply of each good in the market are positive, an individual who trades in the market faces the budget constraint

$$x^s + py^s = x^d + py^d \tag{4}$$

where $p \in \mathbb{R}_+$ denotes the price of y measured by x. Let $\tilde{S} \equiv \{(l_x, l_y; x^d, y^d, x^s, y^s) \in [0,1]^2 \times \mathbb{R}_+^4 : x^s \le l_x^a$ and $y^s \le l_y^a\}$. The individual's decision problem (1)-(4) is equivalent to maximization of function

$$v(s) = (l_x^a - x^s + kx^d)(l_y^a - y^s + ky^d) \tag{5}$$

by choosing $s = (l_x, l_y; x^d, y^d, x^s, y^s) \in \tilde{S}$, which is called a production-trade plan, subject to constraint (4).

Table 1. Three configurations in economy E

Configuration	***Utility***	***Production plan and Trade plan***
A（Autarky）	$u_A = 4^{-a}$	$l_x = l_y = 1/2$； $x^s = x^d = y^s = y^d = 0$
X/Y（sell x and buy y）	$u_X = 4^{-1}kp^{-1}$, if market exists $u_X = 0$， if market does not exist	$l_x = 1$; $x^s = 1/2, y^d = x^s / p$
Y/X（sell y and buy x）	$u_Y = 4^{-1}kp$, if market exists $u_Y = 0$， if market does not exist	$l_y = 1$; $y^s = 1/2, x^d = py^s$

According to Wen Theorem (Wen, 1998)[8], in Economy E, for any $p \in \mathbb{R}_+$, the optimal choice of each individual must be one of the following three configurations[9] (see Table 1). Let $S_1 =$ A, $S_2 =$ X/Y, $S_3 =$ Y/X and $\Delta = \{(\lambda_1, \lambda_2, \lambda_3) \in \mathbb{R}_+^3 : \lambda_1 + \lambda_2 + \lambda_3 = 1\}$. Each vector $\eta = (\eta_1, \eta_2, \eta_3) \in \Delta$ represents a population distribution over the three configurations/professions, where η_j is the share of population choosing S_j. According to the definition of the Walrasian equilibrium, it is easy to obtain the following conclusion[10]:

Theorem 1 (Yang and Ng, 1993, p.60). Given $a > 1$ and $k \in [0,1]$: the Walrasian equilibrium of economy E is $(1,0,0)$ if $k < 4^{1-a}$; the Walrasian equilibrium is $(0, \frac{1}{2}, \frac{1}{2})$ if $k > 4^{1-a}$; the Walrasian equilibrium is a convex combination of $(1,0,0)$ and $(0, \frac{1}{2}, \frac{1}{2})$ if $k = 4^{1-a}$.

So far, we have seen that the Walrasian model provides a clear formulation of the large, decentralized economy and a reasonable prediction of the outcome of the economy, and the network of division of labor satisfying the properties listed in the definition of the Walrasian equilibrium exists and satisfies Pareto optimality. These

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8 See, also, Lemma 2.1 in Yang and Ng (1993, pp.55-57). Because Walrasian regime is assumed, the price $p \in \mathbb{R}_+$, which is determined by the market clearing condition, is a function of all individuals production and trade plans. This implies each individual is actually a player within the game in which her payoff is determined by her own strategy – the production and trade plan – and all the other players' strategies. What is suggested by Wen Theorem is that all strategies available to an individual, except A, X/Y and Y/X , are strictly dominated and therefore can be ignored in the following analysis.

9 In new classical literature, a profile of zero and positive values of decision variables in the individual's decision problem is called a configuration if it is consistent with Wen Theorem. Each configuration represents a possible mode of production and trade that an individual can choose, specified by "what to produce, what to sell and what to buy". It represents autarky, if one chooses to trade nothing; it may represent a profession or a certain pattern of specialization, if one chooses to trade some goods.

10 For economy E, because the preference and the production functions are specified, we can use conditions (C1)-(C3) to solve the equilibrium directly (See Yang and Ng, 1993). A standard procedure to solve the equilibrium by using these conditions is called inframarginal analysis by new classical economists (Cheng and Yang, 2004).

conclusions are no doubt important for the study on division of labor. However, they are not enough to convince people that a competitive market can spontaneously coordinate individuals' decentralized decisions to discover an efficient network of division of labor. The main reason is because the model has not illuminated why and how the equilibrium defined by the new classical economists can be realized in a large, decentralized economy, in which there is not a central planner who can calculate the equilibrium and put it into practice by authority. This question cannot be avoided if one really wants to formalize the function of the market in coordinating division of labor.

Comparing the new classical Walrasian model with the neoclassical model of resource allocation in a competitive market, it can be found that the formulation of the environment and the definition of the equilibrium used in the new classical model are similar to the neoclassical model[11]. It is natural to ask if the Walrasian equilibrium defined by new classical economists can be realized by the Walrasian auctioneer as in the neoclassical model. Unfortunately, the answer is "No". To see this, we assume that $k=1/2$ and $a=2$. According to Theorem 1, the Walrasian equilibrium must be the state where half population produce x, half produce y, and $p=1$ (See Yang and Ng 1993, p59-63 for a detailed analysis). Assume the initial state of the economy is that all individuals choose autarky. If the Walrasian auctioneer gives the first price, say $p=2$, then all individuals will choose Y/X as their optimal choice after comparing the utilities of the three configurations under this price. Individuals' decisions result in a positive excess supply of y and a positive excess demand of x in the market. Observing this, the auctioneer will decrease the price of y. He will have to keep doing this and the structure of division of labor will keep changed until p is decreased to 1. However, when the auctioneer eventually decreases p to 1, there is no difference for an individual to choose between X/Y and Y/X. While no further

[11] See Yang and Ng (1993, pp 39-70) for a complete discussion on the relation between the new classical model and the neoclassical model.

information is available, an individual can choose any of these two options with arbitrary probability. If the result of all individuals' random decisions happens to be the state that half population produce x and the other half produce y, the equilibrium is attained. However, this is an event that happens with a probability of zero. There is not a mechanism available in the Walrasian regime to guarantee that the average frequency of choosing X/Y in the whole population just equal to that of choosing Y/X (Ng 2004, p. 245).

Seeing that the Walrasian model cannot provide a mechanism to explain the realization of the equilibrium network of division of labor[12], new classical economists developed another model, trying to fill the gap. In this model (see Yang and Ng 1993, p.86-93), the determination of division of labor is formulated as a multilateral bargaining game in which each individual makes decision on price and what to sell and to buy by bargaining with all the others. The size of the game equals that of the economy. The outcome of the economy is defined as a strategy profile – a set of all individuals' strategies – that maximizes the Nash product (Nash, 1950). It can be proved that the outcome of the bargaining game coincides with the equilibrium of the Walrasian model, at least in some special cases, such as economy E.

The bargaining model does provide a coordination mechanism of division of labor that is absent in Walrasian model. However, in my opinion, the multilateral bargaining game is not a proper formulation of the large, decentralize economy. Bargaining as a coordination mechanism usually happens in an environment where "no action taken by one of the individuals without the consent of the others can affect the well-being of the others" (Nash, 1950). In this sense, the bargaining model may be a good formalization of the pricing process among a small number of individuals, especially when they are well communicated with each other, such as a firm or a family, but is not able to explain the coordination process of division of labor within a large, decentralized economy. The real economy is too large to bargain. In an

[12] Yang and Ng (1993) noticed that the Walrasian model does not "explicitly spelt out the pricing process" that can coordinate division of labor and is "open to criticism".

economy where millions of people trade thousands of goods among them as the real world we can see, division of labor, as well as resource allocation at the social level, is apparently not a result of bargaining. Assume that you are an economic professor of the university and I am a chef working in the campus center. My son is a student in you class and you are a fan of my food. We have division of labor between us and we exchange our productions in the market. But it is not convincing to say that you choose to be a professional teacher in the university because you have bargained and made an agreement with me. The division of labor between us is the result of some “invisible hand” rather than a bargaining process. It does not solve the problem we are really concerned with.

So far, we have seen that the new classical economics has made some substantial progresses in explaining the emergence of division of labor comparing with the neoclassical economics. However, all current studies by the new classical economists have not really spelt out how division of labor is coordinated and realized in a large decentralized economy. This, however, is the crucial problem of modeling division of labor. This paper attempts to provide an answer.

3. Evolution of division of labor: a static analysis

The equilibrium of division of labor predicted by the new classical models is intuitively reasonable; however, we hope to know whether and how it can be realized in the real world. To answer this question, in this and the next section, I will return to the evolutionary nature of the real economy that has been neglected by the current studies. By doing so, it will be shown that the equilibrium predicted by the new classical economics is supported by evolutionary stability and can be realized by evolutionary processes.

In this section, before we specify the dynamic rules of inheritance, selection and mutation, a static analysis will be adopted first. Dynamic processes of evolution will be formally introduced into the analysis in the next section. The reason of doing a static analysis is to help us predict what a state of the division of labor is possible to be the outcome of the evolutionary dynamics. From an evolutionary perspective, an economy can be regarded as a "field" of evolutionary games where individuals are competing under the law of "survival of the fittest". Each configuration listed in Table 1 is a pure strategy that one can choose, so each individual has the same set of pure strategies $S \equiv \{S_1, S_2, S_3\}$ [13]. Every day, an individual needs to do three things: In the morning, she needs to make a choice from Δ, the set of all probability distributions over S, i.e., to choose a mixed strategy that specifies the probabilities of becoming an autarky individual, an x-specialist and a y-specialist; in the afternoon, she enters the only market to trade with others[14] if she chose to be a specialist; in the evening, she consumes the goods self-provided or/and bought to determine her payoff. The market is a Walrasian regime where prices are determined by the market clearance condition and each specialist is a price taker who chooses the quantity of demand and supply to maximize the utility[15]. It should be noticed that each individual has already determined her profession before she enters the market. So in the market, she can only choose how much to sell and buy, rather than what to sell and buy.

Each $\eta = (\eta_1, \eta_2, \eta_3) \in \Delta$ may represent a mixed strategy that an individual can play, as well as a population distribution over different configurations. In the first case, η_j is the probability of choosing S_j; in the second, η_j is the share of population playing S_j. Denote by $\pi(S_j, \eta)$ the payoff of an individual who plays S_j in the face of a population distribution η. An individual who chooses a mixed strategy $\delta = (\delta_1, \delta_2, \delta_3)$ and faces with a population distribution η has a payoff

[13] In fact, any production-trade plan is a pure strategy that is available to the individual. But because of Wen theorem, it is easy to see that all these pure strategies, except the three configurations, are strictly dominated. Hence, it is natural to limit our discussion on the three configurations.

[14] All specialists trading in the same market implies that the game is of the mode of "playing the field".

[15] The market can be equivalently formulated as an abstract economy (Debreu, 1952) and the Walrasian equilibrium of the market, given the network of division of labor, can be realized by the Nash equilibrium of the abstract economy.

$\pi(\delta,\eta)=\sum_{j=1}^{3}\delta_j\pi(S_j,\eta)$. In economy E, given a population distribution $\eta=(\eta_1,\eta_2,\eta_3)$, if $\eta_2\eta_3>0$, market clearing implies that $p=\frac{\eta_2}{\eta_3}$, and we have $\pi(S_1,\eta)=4^{-a}$, $\pi(S_2,\eta)=\frac{k\eta_3}{4\eta_2}$, and $\pi(S_3,\eta)=\frac{k\eta_2}{4\eta_3}$; if $\eta_2\eta_3=0$, no trade takes place in the market and we have $\pi(S_1,\eta)=4^{-a}$, $\pi(S_2,\eta)=\pi(S_3,\eta)=0$.

Neglecting the specified rules of inheritance, selection and mutation, the following concepts, namely *evolutionarily stable strategy* (ESS) and *naturally stable strategy* (NSS), are broadly used by biologists and economists to predict the outcome of evolution (e.g., Fudenberg and Levine, 1998; Friedman, 1991; Hofbauer and K. Sigmund, 1988; Maynard Smith, 1982; Samuelson, 1997; Young, Peyton, 1998; among others) [16].

Definition 1. A strategy $\eta\in\Delta$ is said to be an *evolutionarily stable strategy*, if for any $\eta'\in\Delta$, $\eta'\neq\eta$, $\exists\bar{\varepsilon}>0$ such that the inequality

$$\pi(\eta',\varepsilon\eta'+(1-\varepsilon)\eta)<\pi(\eta,\varepsilon\eta'+(1-\varepsilon)\eta) \tag{7}$$

holds for all $0<\varepsilon\leq\bar{\varepsilon}$.

ESS is at the heart of the analysis of evolutionary games in a static case. The main idea behind EES is that an evolutionarily stable strategy must be unbeatable (Hamilton, 1967) or uninvadable (Friedman, 1991). I.e., once the strategy has been

[16] The concepts of ESS and NSS were first defined by Maynard Smith and Price (1973) and Maynard Smith (1982) respectively.

adopted by the whole population, any deviant behavior (an invasion of mutants) that is employed by an arbitrarily small fraction of the population can only earn less. This criterion of evolutionary stability can be weakened.

Definition 2. A strategy $\eta \in \Delta$ is said to be a *neutrally stable strategy*, if for any $\eta' \in \Delta$, $\exists \bar{\varepsilon} > 0$ such that the inequality

$$\pi(\eta', \varepsilon\eta' + (1-\varepsilon)\eta) \le \pi(\eta, \varepsilon\eta' + (1-\varepsilon)\eta) \tag{8}$$

holds for all $0 < \varepsilon \le \bar{\varepsilon}$.

Comparing expression (7) and (8), we can see that NSS is a slight generalization of ESS. Instead of requiring that all mutants earn less than the incumbent strategy as ESS does, NSS requires that no mutant earn more than the incumbent (Weibull, 1995, p46). Thus an ESS must be a NSS, but not vice versa. While ESS only considers situations where only one strategy dominates in the equilibrium, the concept of NSS includes the situations where several strategies co-exist at the end of the evolution.

The following theorem shows that the equilibrium network of division of labor predicted by the new classical economics coincides with the outcome of evolutionary games.

Theorem 2. In economy *E*, when $k < k_0 \equiv 4^{1-a}$, $\eta^A \equiv (1,0,0)$ is the only ESS; when $k > k_0$, $\eta^{XY} \equiv (0, \frac{1}{2}, \frac{1}{2})$ is the only ESS[17]; when $k = k_0$, there is no ESS and any

[17] Usually, an ESS η is said to have a *uniform invasion barrier* if $\exists \bar{\varepsilon} > 0$ such that inequality (7) holds for all strategies $\eta' \ne \eta$ and all $0 < \varepsilon \le \bar{\varepsilon}$. A small $\bar{\varepsilon}$ may be sufficient for biological evolution because random mutation happens only very rarely and only for some isolated organism. However, for evolution of division of

strategy is a NSS if and only if it is a convex combination of η^A and η^{XY}.

Proof. See Appendix A.

It is shown above that when $k < k_0$ (or $k > k_0$), autarky (or tossing a coin to determine the direction of specialization) is the only ESS. While $k = k_0$, the payoff obtained from the market is equal to that from autarky. Hence, even all individuals have chosen η^{XY} (or η^A) it is still possible to survival by doing η^A (or η^{XY}). It is clear that there will not be any ESS since both of the two mixed strategies generate the same fitness: they can invade each other and neither can be ruled out by natural selection. In this case, each convex combination of η^A and η^{XY} is a NSS and the economy will randomly wander on the set of neutrally stable states giving an uncertain boundary of the market. Comparing Theorem 2 with Theorem 1, we can see that the equilibrium structure of division of labor defined by new classical economists is exactly as the same as the ESS we have shown above. This result shows that once the network of division of labor is in a state that satisfies the three properties of the Walrasian equilibrium defined by the new classical economists, then it will not be invaded by any mutation which is better fit.

4. Evolution of division of labor: a dynamic analysis

Analysis in the above section does not explicitly take into account of any evolutionary dynamics; however, the fact that the equilibrium of division of labor predicted by Theorem 1 is an ESS implies the possibility that the Walrasian

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labor in human society, since people can coordinate to have sizable group actions, and since in the real world, population is never really infinite, the uniform invasion barrier may have to be larger. This is not a problem here because the uniform invasion barrier $\bar{\varepsilon}$ for η^A or η^{XY} as the ESS equals to 1.

equilibrium defined by the new classical economists may be realized by some certain evolutionarily dynamic processes. To verify this, let's consider an infinitely continuous-time framework, starting at $t=0$. Assume each time point $t \geq 0$ is "one day" in which the individual needs to do the three things described in the above section. Individuals' payoffs and strategies at time t will be observed by individuals in the next day. The law of "survival of the fittest" works in the sense that a strategy is more likely to be imitated by the new generation if it led to a relatively higher payoff than others in the previous.

Particularly, we assume that the rules of imitation and "selection" prevailing in the economy make the share of the population playing any given strategy changes in proportion to its relative payoff or its deviation from the average payoff (Vega-redondo, 1996, p.45). This assumption implies that the variations of population distribution on different professions obey the *replicator dynamics*[18] (RD):

$$\dot{\eta}_j(t) = \eta_j(t)[\pi(S_j, \eta(t)) - \bar{\pi}(\eta(t))]; \quad j = 1,2,3 \tag{9}$$

where $\bar{\pi}(\eta(t)) \equiv \sum_{j=1}^{3} \eta_j(t)\pi(S_j, \eta(t))$ is the average payoff that an individual can obtain at time t.

The following theorem confirms that the Walrasian equilibrium defined by the new classical economics will be realized by the evolutionary process of RD in *almost* all situations.

Theorem 3. Suppose that the evolutionary process in economy E is defined by the dynamic system (9). If $k < k_0 \equiv 4^{1-a}$, the equilibrium network of division of labor,

[18] See Vega-Redondo (1996) for a more complete explanation.

as the outcome of evolution, must be η^A when the economy starts with $\eta_1(0) > 0$, the equilibrium must be η^{XY} when $\eta_2(0)\eta_3(0) > 0$ and $\eta_2(0) + \eta_3(0) = 1$; the structure of division of labor will not change when $\eta_2(0) = 1$ or $\eta_3(0) = 1$. If $k > k_0$, the equilibrium of division of labor, must be η^{XY} when $\eta_2(0)\eta_3(0) > 0$; the equilibrium must be η^A when $\eta_1(0) > 0$ and $\eta_2(0)\eta_3(0) = 0$; the structure of division of labor will not change when $\eta_2(0) = 1$ or $\eta_3(0) = 1$. If $k = k_0$, the equilibrium of division of labor, must be a convex combination of η^A and η^{XY} when $\eta_2(0) \neq 1$ and $\eta_3(0) \neq 1$; the structure of division of labor will not change if $\eta_2(0) = 1$ or $\eta_3(0) = 1$.

Proof. See Appendix B.

Consider a specific case where $k = 0.9$, $a = 1.5$, and the economy starts from $\eta(0) = (0.6, 0.3, 0.1)$. The trajectories of variations in population shares under RD are shown in Figure 1.

Figure 1: Evolution of Division of Labor in RD: a=1.5, k=0.9, initial state=(0.6,0.3,0.1)

Noticing that at any time t there is $\eta_1(t)+\eta_2(t)+\eta_3(t)=1$, we can rewrite dynamic system (9) as:

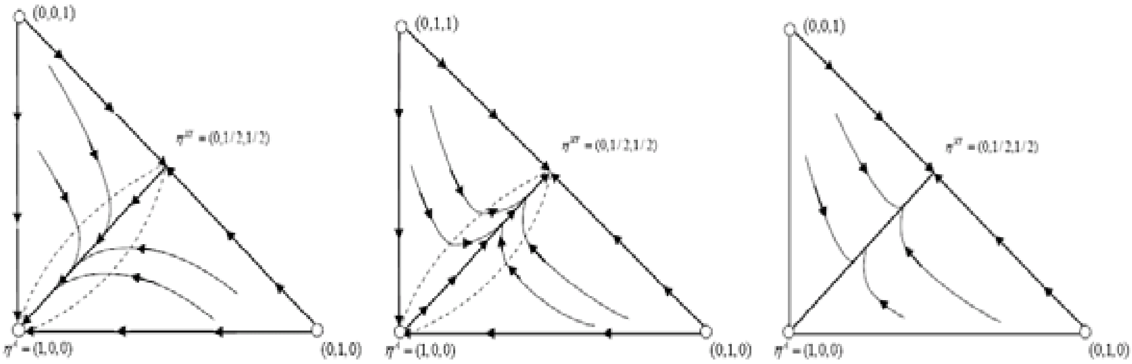
$$\begin{aligned}
\dot{\eta}_1 &= \eta_1[\eta_2(\pi(S_1,\eta)-\pi(S_2,\eta))+\eta_3(\pi(S_1,\eta)-\pi(S_3,\eta))] \\
\dot{\eta}_3 &= \eta_2[\eta_1(\pi(S_2,\eta)-\pi(S_1,\eta))+\eta_3(\pi(S_2,\eta)-\pi(S_3,\eta))] \\
\dot{\eta}_3 &= \eta_3[\eta_3(\pi(S_3,\eta)-\pi(S_1,\eta))+\eta_2(\pi(S_3,\eta)-\pi(S_2,\eta))]
\end{aligned} \tag{10}$$

At the beginning of the economy, there is $\pi(S_3,\eta(0))>\pi(S_1,\eta(0))>\pi(S_2,\eta(0))$. According to (10), in a certain period after the beginning of evolution, population will transfer from A and X/Y into Y/X, and also from X/Y to A. This leads to the increase in the population share of y-specialists and decrease in population share of x-specialists. In this period, because utility difference between X/Y and A is smaller than that between A and Y/X, the population transfer from A to Y/X is faster than population transfer from X/Y to A, the overall tendency of population share of autarky is declining.

Population transferring away from X/Y and population transferring into Y/X will reduce the difference between the population share of y-specialists and that of x-specialists. This leads to an increase in the payoff of the x-specialists and a decrease in the payoff of the y-specialist. The increasing payoff of the x-specialist will first catch up the payoff of autarky, which is a constant independent of the population distribution. This implies $\exists t_1>0$ such that $\pi(S_3,\eta(t_1))>\pi(S_2,\eta(t_1))=\pi(S_1,\eta(t_1))$. At t_1, population transfer from X/Y to A stops but there are still population transfers from A to Y/X and from X/Y to Y/X. After t_1, The difference between population share of y-specialists and x-specialists keeps decreasing and the payoff of the x-specialist keeps going up until it equals to the payoff of the y-specialist. This implies that $\exists t_2 > t_1$ such that for $t \in (t_1, t_2)$ there is $\pi(S_3, \eta(t)) > \pi(S_2, \eta(t)) > \pi(S_1, \eta(t))$ and for $t \in [t_2, \infty)$ there is $\pi(S_3, \eta(t_2)) = \pi(S_2, \eta(t_2)) > \pi(S_1, \eta(t_2))$. According to (10), in the period (t_1, t_2), there must be population transfer from A to both X/Y and Y/X , and population transfer from X/Y to Y/X. In the period $[t_2, \infty)$ there must be population transfer from A to X/Y and Y/X but no population transfer between X/Y and Y/X; the population share of x-specialists and y-specialists keeps equal. (See Figure 1.)

Figure 2 is the phase diagram of dynamic system (9), which gives an overall description of the evolutionary dynamics of division of labor under RD.

Figure 2: Dynamics of the evolution of division of labor in economy E



Case 1: $k<k_0$ Case 2: $k>k_0$ Case 3: $k=k_0$

Theorem 3 shows that the outcome of evolution depends on the initial state of the economy when the evolutionary process obeys RD. The Walrasian equilibrium defined by the new classical economics can be attained by RD in most cases, but may not be attained when the economy starts from some special states. For example, when the economy starts from a state of pure autarky, i.e. $\eta(0) = (1, 0, 0)$, the economy will always stay in this state and specialization and division of labor will never appear in the economy. This is true under RD because a strategy that does not appear in the initial state of the evolution will never be adopted in the whole process of evolution. However, it is apparently not a phenomenon that fits the reality. To avoid this problem, we need to introduce another element of evolution, mutation, into the analysis.

There are several approaches to formulate mutations in an evolutionary process. In this paper, I will assume mutations happen in the way that at any time $t \geq 0$, each individual is subject to the same independent probability $r \in (0,1)$ to adopt some new strategy irrespective of the rules of inheritance and selection (Vega-redondo, 1996, p77). Particularly, I assume that the two pure strategies of specialization – X/Y and Y/X – are adopted by the mutant with the same probability of 0.5. This strategy, taken by the individuals when they mutate, can be regard as the outcome of either unconscious decision made by some independent individuals or conscious decisions made by a group of individuals in communication. With this simple assumption, I ignore the questions such as who will be the mutants, why they mutate and how they interact to decide the mutation strategy. It will be an interesting and important work to think of these questions to clarify the micro mechanism that gives rise to a certain type of mutation. But because the focus of this paper is to check whether the equilibrium will be realized under a given evolutionary process, it is not my target here to answer these questions.

The Replicator Dynamics with this type of mutations (RDM) can be formulated as following:

$$\begin{cases} \dot{\eta}_1(t) = (1-r)\eta_1(t)[\pi(S_1, \eta(t)) - \bar{\pi}(\eta(t))] - r\eta_1(t) \\ \dot{\eta}_2(t) = (1-r)\eta_2(t)[\pi(S_2, \eta(t)) - \bar{\pi}(\eta(t))] + r(0.5 - \eta_2(t)) \\ \dot{\eta}_3(t) = (1-r)\eta_3(t)[\pi(S_3, \eta(t)) - \bar{\pi}(\eta(t))] + r(0.5 - \eta_3(t)) \end{cases} \tag{11}$$

It is easy to see that in this dynamic system, all trajectories converge at $\eta^A \equiv (1,0,0)$ as $t \to \infty$, if $k < k_0$; all trajectories converge at $\eta^{XY} \equiv (0,\frac{1}{2},\frac{1}{2})$ as $t \to \infty$, if $k > k_0$; all trajectories converge at the convex combinations of η^A and η^{XY} as $t \to \infty$, if $k = k_0$. Thus we have:

Theorem 4. Suppose that the evolutionary process in economy E is defined by the dynamic system (11). If $k < k_0 \equiv 4^{1-a}$, the equilibrium of division of labor, as the outcome of evolution, must be $\eta^A \equiv (1,0,0)$; If $k > k_0$, the equilibrium of division of labor must be $\eta^{XY} \equiv (0,\frac{1}{2},\frac{1}{2})$; If $k = k_0$, the equilibrium of division of labor must be a convex combination of η^A and η^{XY}.

Theorem 4 shows that the Walrasian equilibrium defined by the new classical economics coincides with the outcome of the evolution process (11) no matter where the economy starts. Comparing evolution process (11) with (9) or (10), the only difference is that (11) is a more realistic description of the real evolutionary mechanism because it involves not only inheritance and selection, but also mutation. This implies that all the three elements – inheritance, selection and mutation – are necessary parts of the coordination mechanism that can guarantee the efficient network of division of labor to be realized under any possible initial state of the economy. For example, when the economy starts from a pure-autarky state, there will be no evolution of division of labor if no mutation happens in the economy. The mutation here provides an approach for the economy to escape from the trap of autarky.

The trajectories of the evolution of division of labor under RDM are similar to those under RD in most situations. But if the economy starts from a state where most individuals are autarky, RDM, the evolutionary process with mutations (see Figure 3), is more efficient than RD (see Figure 4), the evolutionary process without mutations, in approaching the equilibrium network of division of labor. Although the population share of the mutant is small in the economy, say $\gamma = 0.05$, the behavior of mutants can largely enhance the efficiency of the coordination mechanism in the economy.

Figure 3: Evolution of Division of Labor in RDM: a=1.5, k=0.9,r=0.05, initial state=(0.9;0.08;0.02)

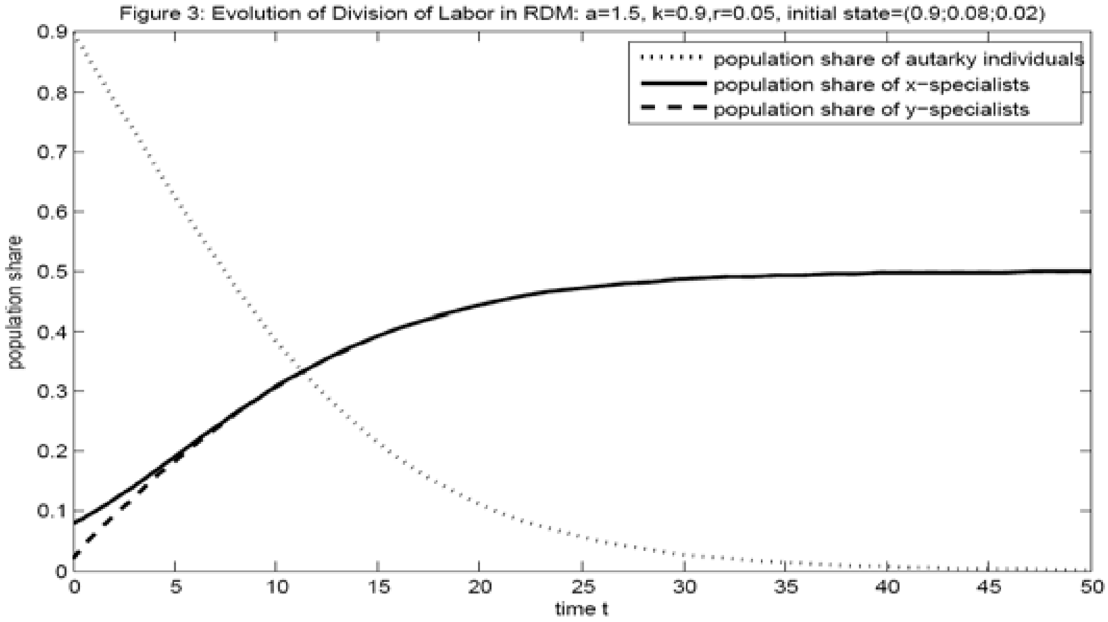
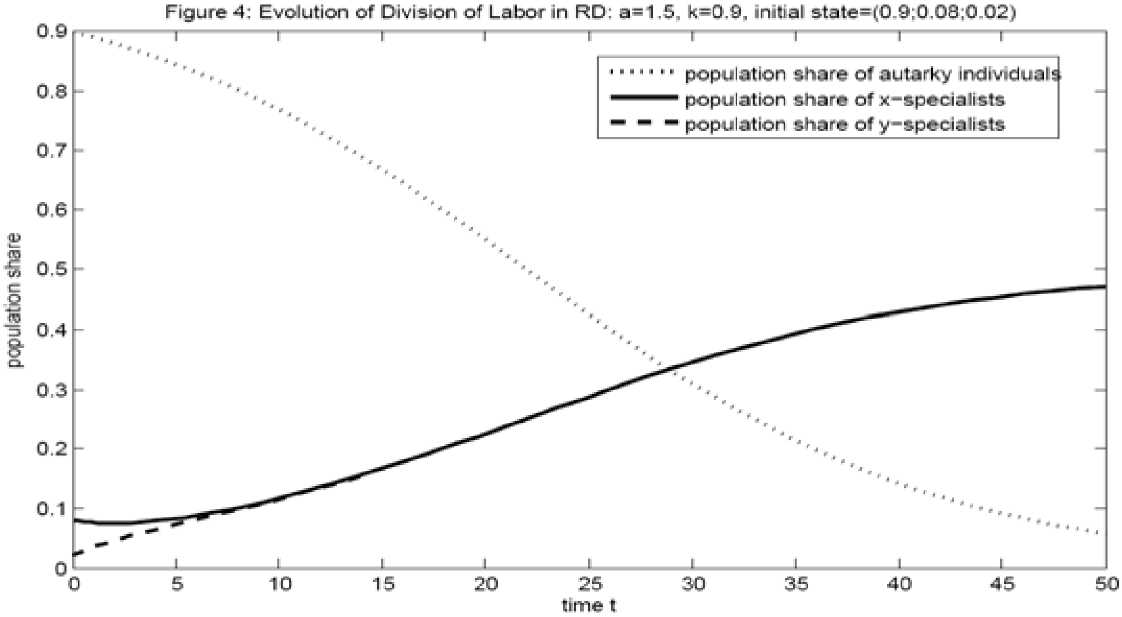


Figure 4: Evolution of Division of Labor in RD: a=1.5, k=0.9, initial state=(0.9;0.08;0.02)



To sum up, we can see that our model supports the central idea of classical and new classical economics that “the function of the market is not only to allocate resources for a given network structure of division of labor, but also to coordinate all individuals’ decisions in choosing their patterns of specialization to utilize positive network effects of division of labor net of transaction costs” (Sun, Yang and Yao, 2004). New classical economists have had in their mind that an efficient network of division of labor that satisfies the properties C1-C3 will be the outcome of the economy; however they did not explicitly spell out what mechanism is coordinating the population distribution to attain the equilibrium. This paper formally provides a possible answer to this question.

5. Concluding remarks

Division of labor is one of the most important features of human society. Although its significance was emphasized by Adam Smith (1776) hundreds years ago, this topic has been ignored by mainstream economics for a long time (Stigler, 1976; Yang, 2001, 2003). New classical economists desire to resurrect the classical spirit in a neoclassical body. However, as shown in Section 1, the current analytical framework of the new classical economics, which is inherited from the neoclassical economics, is not able to explicitly explain how individuals’ decisions on specialization are coordinated and how division of labor is realized in a large and decentralized economy.

The failure of new classical economics is due to the unavailability of a market mechanism that can coordinate population transfer among different professions to attain the equilibrium. The evolutionary elements existing in the real economy, which have been neglected by both neoclassical and new classical economics, provide such a mechanism. By introducing the evolutionary elements, including imitation (inheritance), selection and mutation, into the analysis of division of labor, we can see that the equilibrium network of division of labor predicted by inframarginal analysis can be realized by the outcome of evolution in a large, decentralized economy. In the static analysis, we have shown that the equilibrium network of division of labor can be realized by ESS and NSS. In the dynamic analysis, we further proved that the equilibrium network of division of labor can be realized by the outcome of evolutionarily dynamical processes, such as Replicator Dynamics. It is also shown that the mutation is important in the evolution because it provides a mechanism that can help the economy escape from an initial state without division of labor. These conclusions imply that the three inherent elements of evolution construct an "invisible hand" that can coordinate individuals' decentralized behaviors to obtain an efficient spontaneous order of division of labor.

The market is in itself evolutionary. This fact has been noticed by economists for several centuries; however, the evolutionary features of the real economy have received formal treatment only for several decades. The paper suggests that if we hope to explain the realization of an efficient "resource allocation" at a general level, which includes not only allocation of resource under a given network of division of labor but also the allocation of population over different professions (i.e. the division of labor itself), it seems useful and necessary to introduce the evolutionary features of the market into formal analysis. This paper is based on a simple economy and a specific evolutionary process; however, the main conclusions may be generalized to other economies and other evolutionary processes. Division of labor is affected by human conscious choice which is more than just random mutation and natural selection. This aspect of the evolution/coordination will be addressed in another paper.

Appendix A: Proof of Theorem 2.

Suppose $k < k_0$. For any $\lambda = (\lambda_1, \lambda_2, \lambda_3) \in \Delta$, $\lambda \neq \eta^A$, and any $\varepsilon \in (0,1)$, let

$\tilde{\eta} \equiv \varepsilon\lambda + (1-\varepsilon)\eta^A = (\varepsilon\lambda_1 + 1 - \varepsilon, \lambda_2, \lambda_3)$. We have $\pi(\eta^A, \tilde{\eta}) = u(A) = 4^{-a}$, and

$\pi(\lambda, \tilde{\eta}) = [\varepsilon\lambda_1 + 1 - \varepsilon]\pi(S_1, \tilde{\eta}) + \lambda_2\pi(S_2, \tilde{\eta}) + \lambda_3\pi(S_3, \tilde{\eta}) = [\varepsilon\lambda_1 + 1 - \varepsilon]4^{-a} + [\lambda_2 + \lambda_3]k/4$.

Because $4^{-a} > k/4$, we have $\pi(\lambda, \tilde{\eta}) < \pi(\eta^A, \tilde{\eta})$ for any $\varepsilon \in (0,1)$. It is easy to see that in this situation, η^A is the only ESS. The first conclusion is proved.

Suppose $k > k_0$. For any $\lambda = (\lambda_1, \lambda_2, \lambda_3) \in \Delta$, $\lambda \neq \eta^{XY}$, and any $\varepsilon \in (0,1)$, let $\tilde{\eta} \equiv \varepsilon\lambda + (1-\varepsilon)\eta^{XY} = (\varepsilon\lambda_1, \varepsilon\lambda_2 + (1-\varepsilon)/2, \varepsilon\lambda_3 + (1-\varepsilon)/2)$.

We have $\pi(\eta^{XY}, \tilde{\eta}) = \frac{1}{2}[\pi(S_2, \tilde{\eta}) + \pi(S_3, \tilde{\eta})] = \frac{k}{8}[t + t^{-1}]$ and $\pi(\lambda, \tilde{\eta}) = \lambda_1 4^{-a} + \frac{k}{4}[\lambda_2 t + \lambda_3 t^{-1}]$,

where $t \equiv \dfrac{\varepsilon\lambda_3 + (1-\varepsilon)/2}{\varepsilon\lambda_2 + (1-\varepsilon)/2}$. Because $4^{-a} < k/4$, we have $\pi(\lambda, \tilde{\eta}) < \frac{k}{4}[\lambda_1 + \lambda_2 t + \lambda_3 t^{-1}]$.

In order to obtain $\pi(\eta^{XY}, \tilde{\eta}) > \pi(\lambda, \tilde{\eta})$, we only need inequality

$$(\frac{1}{2} - \lambda_2)t^2 - (1 - \lambda_2 - \lambda_3)t + (\frac{1}{2} - \lambda_3) \geq 0$$

(12) hold. There are five cases to discuss: (a) $\lambda_2 = \lambda_3 < 1/2$; (b) $\lambda_3 < \lambda_2 \leq 1/2$; (c) $\lambda_2 < \lambda_3 \leq 1/2$; (d) $\lambda_3 < 1/2 < \lambda_2$; (e) $\lambda_2 < 1/2 < \lambda_3$. For Case (a), it is easy to see that inequality (12) holds for any $t > 0$, i.e. $\pi(\eta^{XY}, \tilde{\eta}) > \pi(\lambda, \tilde{\eta})$ holds for any $\varepsilon \in (0,1)$. For Case (b), inequality (12) holds for any $t \in (-\infty, 1] \cup [\frac{1 - 2\lambda_3}{1 - 2\lambda_2}, \infty)$. Because for any $\varepsilon \in (0,1)$ there must be $0 < t < 1$, we have $\pi(\eta^{XY}, \tilde{\eta}) > \pi(\lambda, \tilde{\eta})$ holds for any $\varepsilon \in (0,1)$.

This proves that η^{XY} is an ESS. It's easy to see that any other mixed strategy is not an ESS in this situation.

Suppose $k = k_0$. For $\forall \eta, \eta' \in C(\eta^A, \eta^{XY}) \equiv \{\lambda \in \Delta : \exists \alpha \in [0,1], \lambda = \alpha\eta^A + (1-\alpha)\eta^{XY}\}$, we have $\pi(\eta,\eta') = \pi(\eta',\eta) = \pi(\eta,\eta) = \pi(\eta',\eta')$. Given some $\forall \eta \in C(\eta^A, \eta^{XY})$, for any $\lambda = (\lambda_1, \lambda_2, \lambda_3) \in \Delta$, $\lambda \notin C(\eta^A, \eta^{XY})$, and any $\varepsilon \in (0,1)$, let $\tilde{\eta} \equiv \varepsilon\lambda + (1-\varepsilon)\eta$. We have $\pi(\eta, \tilde{\eta}) = \pi(\eta^A, \tilde{\eta}) = 4^{-a}$, and

$$\pi(\lambda,\tilde{\eta}) = \lambda_1 \pi(S_1,\tilde{\eta}) + \lambda_2 \pi(S_2,\tilde{\eta}) + \lambda_3 \pi(S_3,\tilde{\eta}) = \lambda_1 4^{-a} + \frac{k}{4}[\lambda_2 \tilde{t} + \lambda_3 \tilde{t}^{-1}],$$

where $\tilde{t} \equiv \dfrac{\varepsilon\lambda_3 + (1-\varepsilon)\eta_3}{\varepsilon\lambda_2 + (1-\varepsilon)\eta_2}$. Thus we have

$$\lambda_2 + \lambda_3 - (\lambda_2 \tilde{t} + \lambda_3 \tilde{t}^{-1}) =$$

$$\varepsilon(1-\varepsilon)(\lambda_2 - \lambda_3)(\lambda_2\eta_3 - \lambda_3\eta_2) + (1-\varepsilon)^2(\eta_2 - \eta_3)(\lambda_2\eta_3 - \lambda_3\eta_2).$$

Because $\eta_2 = \eta_3$, $\lambda_2 \neq \lambda_3$ and $4^{-a} > k/4$, there must be $\pi(\lambda,\tilde{\eta}) < \pi(\eta^A,\tilde{\eta})$ for any $\varepsilon \in (0,1)$. #

Appendix B: Proof of Theorem 3.

Because $\eta_1(t)$ is not independent of $\eta_2(t)$ and $\eta_3(t)$, we can neglect $\eta_1(t)$ in the analysis. We only consider the case where $k > k_0$ since the proof is similar when $k < k_0$ or $k = k_0$. If at the start of the process there is $\eta_2(0)\eta_3(0) > 0$, we have $\eta_2(t)\eta_3(t) > 0$, $\pi(S_1, \eta(t)) = 4^{-a}$, $\pi(S_2, \eta(t)) = \dfrac{k\eta_3(t)}{4\eta_2(t)}$, and $\pi(S_3, \eta(t)) = \dfrac{k\eta_2(t)}{4\eta_3(t)}$ for $\forall t \geq 0$. Substitute these items into (9), we can obtain

$$\begin{cases} \dot{\eta}_2 = 4^{-1}k\eta_2[\eta_3/\eta_2 - 4^{1-a}(1-\eta_2-\eta_3)/k - \eta_2 - \eta_3] \\ \dot{\eta}_3 = 4^{-1}k\eta_3[\eta_2/\eta_3 - 4^{1-a}(1-\eta_2-\eta_3)/k - \eta_2 - \eta_3] \end{cases}.$$

It is easy to verify that in this situation, all trajectories converge at $\eta^{XY} \equiv (0, \frac{1}{2}, \frac{1}{2})$ as $t \to \infty$. If at the start of the process, there is $\eta_1(0) > 0$ and $\eta_2(0) = 0$ (or $\eta_3(0) = 0$), we have $\eta_2(0) = 0$ (or $\eta_3(0) = 0$), and $\pi(S_1, \eta(t)) = 4^{-a} > \pi(S_2, \eta(t)) = \pi(S_3, \eta(t)) = 0$ for $\forall t \geq 0$. Thus trajectories will converge at η^A. If at the start of the process, there is $\eta_2(0) = 1$ (or $\eta_3(0) = 1$), we have $\eta_2(t) = 1$ (or $\eta_3(t) = 1$), $\eta_1(t) = 0$ and $\pi(S_2, \eta(t)) = \pi(S_3, \eta(t)) = 0$ for $\forall t \geq 0$. The structure of division of labor will not change.#

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