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By

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This book first published 2016

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-4438-8516-9
ISBN (13): 978-1-4438-8516-4

DEDICATION

This book is dedicated to my wife Laura, my children Matteo and Pietro, and my mother Yolanda Carrera.

To my father Miguel Angel, and my brothers Mayo and Luis.

Because they are all the love in my life!

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PREFACE

Contemporaneous growth theory is especially interested in explaining why some countries grow and flourish while other countries appear to stagnate and not grow at all. Explaining growth as endogenous to agents' decisions and explaining very different growth paths across countries make it natural to consider the political economy of growth. Political Economy models attempt to explain economy growth outcome as reflecting endogenous political decisions. Accumulation of physical and human capital should be significantly affected by political decisions, so political economy of growth naturally fits in endogenous growth theory. In this work, we are particularly interested in explaining the influence of political decisions on the agents' decisions. We will analyze poverty traps as a state of stagnation in the growth of an economy, and the possibility of overcoming them through correct policy decisions that are reflected in correct and rational choices made by rational economic agents. However, in this work, we do not follow a standard approach. Our main tool is evolutionary game theory. The economic agents, attempting to maximize their own expectations, and looking at the behavior of institutions and that of other individuals, choose their own behavior. In this sense our analysis rises from the behavior of the economic agents.

Standard growth theory teaches us that poverty traps are stable-low level balanced growth paths to which economies gravitate due to adverse initial conditions or poor equilibrium selection. In other words, societies fail to take off into sustained growth because they started poor (e.g., low longevity or poor human capital as in Azariadis and Drazen, 1990), or because they cannot create institutions that coordinate their investments successfully. This thesis explains this pernicious form of coordination failure as a game between economic agents: leaders and followers investing to become high-profile. Rates of return of high-profile leaders depend on average high-profile followers (i.e. human capital), and rates of return on high-profile followers depend on aggregate high-profile leaders' investments (i.e. innovative firms or R&D). The outcome is a self-confirming equilibrium in evolutionarily stable strategies in which unsuccessful players imitate successful ones. This equilibrium has the following interesting property:

> *In poor economies with a large fraction of low-profile followers or low-profile leaders, imitative strategies do not support a take-off into sustained growth. To achieve that take-off, the society should subsidize the cost of education and/or skill premia through a tax system on income until the economy builds a critical mass of high-profile economic agents.*

Hence, we consider a baseline model in which we apply two different imitation rules. The baseline model studies an evolutionary game with two asymmetric populations where players from each population are paired with members of the other population. We consider imitation as the facilitator of evolutionary dynamics, resulting in evolutionarily stable strategies. We present two imitation models. In the first model, dissatisfaction drives imitation. In the second model, agents imitate the successful. In the first model, we use a simple reviewing rule, while in the second model, we use a proportional imitation rule where switching depends on agents comparing their payoffs to others' payoffs. We show that such imitation is approximated by a replicator dynamic system, following which we apply the well-known relationships between stability of stationary states, evolutionarily stable strategies (ESS), and Nash equilibria. We characterize the evolutionarily stable strategies of our two asymmetric populations and we show that a mixed strategy profile distribution of inhabitants can be an ESS if it is the strict Nash equilibrium. We offer one clear conclusion: whom an agent imitates is more important than how an agent imitates.

To reach our results, in this essay, we considered that the imitative behavior of the economic agents is the facilitator of the evolutionary dynamics of the economy, with this resulting in evolutionarily stable strategies.

So, this work applies evolutionary game theory to several models concerning the notions of economic agents and poverty traps. That is:

First, a coordination game interpreted as a game between economic agents; namely a leader and a follower. The leader must hire the follower and each player can be either a high or a low profile economic agent. The follower can decide to become the high profile type by incurring some training costs. Both players must also pay some income tax. A play that is stuck in the low-level or inefficient equilibrium is interpreted as being in a poverty trap. Self-confirming equilibria are analyzed before looking at the replicator dynamics driven by imitation. We show that the economy can be located in a low-level or high-level equilibrium, both of which are evolutionarily stable strategies against the field. Furthermore, we show that to overcome the poverty trap, there exists a threshold number of high-profile economic agents which depends mainly on training costs (or education costs), skill premia or bonuses for skillful agents, and income taxes.

Second, an economy with two types of firms (innovative and non-innovative) and two types of workers (high-skilled and low-skilled), where the workers' decisions are driven by imitative behavior, while firms' decisions depend on the number of high-skilled workers. We show that such an economy's evolution depends on the initial distribution of the firms. The multiple equilibria of this model can be characterized either by a continuum of high level steady states or only one low level steady state, for which there exists a threshold level to be overcome in order to attain the higher level equilibria. We show that in each high level equilibrium, a percentage of innovative firms coexist with a percentage of non-innovative firms, and a set of high-skilled workers coexist with a set of low-skilled workers. But if the initial percentage of innovative firms is lower than the threshold value, then the economy devolves to a low level equilibrium wholly composed of non-innovative firms and low-skilled workers.

Third, we consider that the decisions of both firms and workers are driven by imitating successful strategies. Firms and workers should decide whether to be high-profile or low-profile agents by following an imitative behavioral rule given the current state of the economy, characterized by the distribution of strategies. We apply evolutionary game theory to find the system of replicator dynamics, and characterize the low-level and high-level equilibria as evolutionarily stable strategies (ESSF) against the field. We introduce this concept to analyze the magnitude of change required in the initial conditions for this to be effective as an incentive for change in the attitude of the agents. In some ways, the measures are something very close to the inertia of a body in movement. We show that when the current state of the economy is in the basin of attraction of the poverty trap, players should play against the field "if they want to change the *status quo*". The threshold level to overcome the poverty trap can be lowered if there is an appropriate policy using income taxes, education costs and skill premia.

Moreover, as it is well known, individual income depends on both the education of the workers and the salary paid at each education level. The question about what happened in Mexico makes sense, where the export-manufacturing industries (maquiladoras), opened in the country after the implementation of the NAFTA, pay higher wages compared to domestic firms (see Harrison, and Lypsey (1996). The high salaries pulled workers out of school at younger ages, inhibiting their skill acquisition (for an interesting study analyzing this topic, see D. Atkin, 2010). So, nevertheless, the improvement in employment levels and the rising wages in the country that the establishment of these firms has implied are not the source of sustainable growth that the country requires, because they do not employ highly skilled workers. In many cases, it is domestic high-tech firms that play this role. Students may choose to stay in school for longer, but only if the firm will reward the additional skill acquisition. Therefore, we study the replicator dynamics with Pigovian subsidy and payoff taxation as a mechanism of equilibrium selection to overcome the poverty trap.

Fourth, this essay studies the dynamic complementarities of non-homogeneous firms and workers that face some costs and skill-biased technical change. We show that the profits of innovative firms increases as the supply of skilled workers increases by decreasing production costs and even lowering prices, all of this through time. There is a threshold of the share of skilled workers such that a firm prefers to be innovative than non-innovative. On the other hand, workers follow an imitative behavior to choose their skill profile. We show that, as the share of innovative firms is large enough, then the share of skilled workers in equilibrium depends to the reviewing rate of those unskilled workers. Moreover, the Mexican government intervention is justified only by the given incentives to the non-innovative firms to become innovative, with the objective of increasing the share of innovative firms, but once the economy is in the path of a high equilibrium, such an intervention should be canceled.

Finally, I really want to acknowledge to Elvio Accinelli and Lionello Punzo, since they gave me a taste for economic theory and the theory of games as a tool to understand the strategic foundations of economic growth and development. I am also indebted to Costas Azariadis, Samuel Bowles and Herbert Gintis for their helpful comments and frequent guidance to improve this research. To the faculty members of the Department of Economics at the University of Siena. To Facultad de Economia UASLP and FAI 2015 at UASLP Mexico for their financial support.

Chapter One

Introduction: Evolutionary Poverty Traps

Economists have used the idea of economic agents to conceive of agents as decisionmakers endowed with preferences, who form expectations, and face particular constraints. The idea of the economic agent incorporates persons, firms, and other entities such as nonprofit organizations and governments. The essential characteristic of an economic agent is not its physical form but rather its status as a decisionmaker. An agent as a decisionmaker carries within it a straightforward answer to the question of how agents interact. Agents interact through their chosen actions. An action chosen by one agent may affect the actions of other agents through three channels: constraints, expectations, and preferences.

In this book we argue that, it is the strategic behavior of economic agents which can lead an economy to either a high or low level equilibrium, where a low-level equilibrium is a situation where economic performance is low on most relevant counts (GDP per capita, Human Capital, R&D, Innovation, etc.). A poverty trap is a low-level equilibrium defined as any self-reinforcing mechanism which causes poverty to persist (see Azariadis and Stachurski, 2005), and in which economic agents suffer from persistent underdevelopment.

So, the aim of this book is to develop an evolutionary model applying evolutionary game theory to the notion of poverty traps. We study the evolution of the social norm of being either a high-type or low-type in a dynamic environment, where agents are driven by imitative behavior. History matters because given initial conditions, agents imitate according to their current success in payoffs and the current profile of economic agents in the economy. We define a poverty trap as an evolutionarily stable strategic profile and steady state of the replicator dynamics. In this vein, Sanchez Carrera (2012) shows that in poor economies with a large fraction of low-type agents, imitative strategies do not support a take-off into sustained growth. To achieve this take-off, the society should subsidize the critical parameters of the expected payoffs, such that economic agents may change the initial conditions and the economy receives a critical mass of high-type economic agents, so as to overcome the poverty trap.

The number of papers applying game theory to biological problems are in the thousands, since integrated bioeconomic models combining both biological processes (e.g. plant growth, soil nutrient flows, livestock production, agroforestry) and human behavior (i.e. imitative behavior) are increasingly found to be quite useful both as decision support tools and for ex-ante assessment of the performance of new technologies and policies. Although biology clearly supports the conjecture of complementarities (even gens, bacteria, organelles and viruses can be engaged in games of cooperation and conflict), there does not appear to be any formal estimation of the gains from imitative behavior (see Nowak and Sigmund 2004). So what we learn from biological games to economics comes from an evolutionary analysis of an economy where there are both strategic interactions and population structures. This conceptually simple game offers only two strategies (either a type) and four outcomes (either coordinated or not). These prospective general equilibrium effects underscore the importance of an improved understanding of evolutionary poverty traps in systems characterized by imitative economic agents, incomplete markets and non-constant returns to productive assets due to their underlying biology. How to break out of relief traps is indeed a key issue facing many countries today.

Here, we develop a model of poverty traps by using evolutionary game theory. The evolutionarily stable strategy (ESS) developed by biologist John Maynard Smith is the most widely used solution concept in evolutionary games. An incumbent strategy x is played within a population that is susceptible to invasion by a mutant strategy y. Individuals within a large population are paired randomly to play the game. Payoffs are given in terms of reproductive fitness.[1] Although evolutionary stability is the best known concept in evolutionary game theory, it is a static concept that is unable to describe the dynamics of behavioral systems. So studying the replicator dynamics of a system is an increasingly utilized tool for understanding the evolution, for example, of institutions and social norms, providing many applications in development economics (see Gintis 2009). Hence, the aim of this paper is to use the replicator dynamics to study the evolutionary stability of poverty traps, since analyzing the replicator

[1]When we talk of an ESS, we usually model strategies as phenotypes, where it is not trial and error, but an agent programmed with a given strategy, and then it is the survival of the fittest.

dynamics of a system allows one to understand the increasing and decreasing propensity of different behaviors as they meet within a population, leading an economy either to a high-level equilibrium or a low level poverty trap. The equilibrium concept used in the replicator dynamics framework is loosely called dynamic stability, often referred to more specifically as asymptotic stability (Weibull 1995). Intuitively, the state of a population playing a given mixed or pure strategy x is dynamically stable if any small change in the strategy mix does not lead the dynamics away from returning back to x. The following relationships between dynamic stability, evolutionarily stable strategies, and Nash equilibria hold for a general class of games: Every dynamically stable point is Nash equilibrium, but not every Nash equilibrium is dynamically stable. Moreover, every ESS is dynamically stable, but not all dynamically stable population states are ESSs. Thus the ESS is the most stringent of the three concepts, dynamic stability is the second, and the Nash equilibrium is the third.

The model presented here explains how imitative behavior as a culture of cooperation must attain an economic outcome which can lead to a time-stable distribution of economic agents that leads the economy into a social poverty trap. By this, we mean a situation in which the process of cultural transmission between types of economic agents may lead to different long-run levels of equilibria due to certain initial conditions. So we show that a poverty trap is an evolutionarily stable strategic profile of economic agents.

This paper draws from related literature: models of poverty traps and multiple equilibria, and literature on evolutionary game theory and cultural transmission in repeated interactions. This paper relates to several literatures in economics. First, in spirit, the model presented here is similar to that of Accinelli and Carrera (2012). In their article, Accinelli and Carrera develop a model in which several equilibria of economic agents' types can arise. Investment in education can help reach a higher level equilibrium, and therefore transmit more assets to the next generation. However, because of imperfect information, and because the cost of education is indivisible, poor individuals do not invest in human capital, and therefore leave bequests too low for the young to invest in education, i.e. by imitative behavior, they decide to not invest in education. Poor individuals are therefore stuck in the low equilibrium of unskilled jobs (see the seminal paper by Nelson and Phelps 1966; Schultz 1975). More recent studies develop different models to prove that high-skilled labor and high-technological firms are complements in order to obtain a high-level equilibrium (particularly, see Acemoglu 1997, 1998). Acemoglu (1997) considers the same type of interdependence under heterogeneous individuals' human capital. Acemoglu (1998) focuses on skill-biased technological progress and inequality growth between and within groups of skilled and unskilled workers, paying particular attention to common situations in which workers accumulate general skills to prepare for the obsolescence of their technology (firm-)specific skills due to technological progress.

Second, significant articles in game theory have been devoted to the possibility of sustaining cooperation in repeated games (these results are usually referred to as Folk Theorems). Folk Theorems essentially mean that patient players have the potential to sustain higher equilibrium payoffs than impatient players. This is the line, for instance, adopted by Poulsen and Svendsen (2005), who model social capital as the ability to cooperate in a one-shot prisoner's dilemma game. They focus on the possible emergence of a unified norm of cooperation. We instead focus on the possibility of the emergence of heterogenous time-preferences. Contrary to Krusell and Smith (1998) and Doepke and Zilibotti (2008), this paper focusses on the ability to imitate and cooperate as the main channel through which patience affects economic outcome.

More closely related is the literature on learning and adaptive dynamics in games (see Maynard Smith 1982; Maynard Smith and Price 1973, for the early seminal works in this area). One branch of this literature (for example, Young 1993, 2001; Kandori, Mailath and Rob 1993; Binmore and Samuelson 1997) investigates stable patterns of behavior as limit points of various adaptive dynamics. Following the literature on cooperation in repeated games, we model the ability of a high or low type of individual to cooperate by strategic complementarities. In a context of complementarities, cooperation might be beneficial and would therefore help to reach a higher economic outcome from the relationship. But, also, cooperation by strategic complementarities can be risky when the initial conditions are such that adopting the lowest type is the best action, and so the economy can be caught in a low-level equilibrium. These considerations are studied in the present book.

Steven Durlauf has enriched the modeling of poverty traps by adding a spatial dimension: the idea that an agent's socioeconomic outcomes depend upon the composition of the various groups of which she is a member over the course of her life. That is, the decision for an agent to acquire an education strongly depends on the prior existence of other educated members in a group. This interdependence of behavior induces "neighborhood effects", which generate different types of groups that have different steady states (with/without educated members). This interdependence may be intertemporal, i.e. it affects future social interactions.[2] It is this concept of neighborhood effects that, for Durlauf, allows for the understanding of why poverty traps exist and persist. Hence, poverty traps are defined as a community of economic agents that are composed initially of poor members with low-profiles that remain in the low-level equilibrium over generations (Durlauf, 2003).

Poverty traps can therefore arise across geographical locations, and within dispersed collections of agents affiliated by cultural facts and institutions. Group outcomes are then summed up progressively from the level of the agent.

In this vein, Samuel Bowles has built the seminal concept of 'institutional poverty traps', which emphasizes that coordination failures and poverty traps are induced by the presence of specific institutions. Bowles defines institutions as conventions in which members of a population typically act in ways that maximize payoffs given the actions taken by others, such that the process supports continued adherence to the conventions (Bowles, 2006:118).

Polterovich (2008) points out that the formation of institutional traps due to the economic agents with low-profiles who conform to specific strategies is one of the main obstacles to improving economic performance. He defined an institutional trap as a stable yet inefficient equilibrium in a system, where agents choose a norm of behavior (an institution) among several options. It is usually implied that multiple equilibria prevail in the system, and that an institutional trap is Pareto dominated. As with any other norm, an institutional trap's stability means that a system absorbing a small external shock will remain in the institutional trap, having perhaps slightly changed its parameters, and will return to the inefficient equilibrium state once the source of destabilizing pressure is removed. Individuals or small groups of people lose if they deviate from an institutional trap. However, the simultaneous adoption by all agents of an alternative norm may be Pareto improving. Thus the lack of coordination is the main cause of the institutional trap's stability.[3]

Hence, the types of economic agents and their neighborhoods can explain whether a low-level or high-level equilibrium obtains for an economy. We study the idea of neighborhood effects by considering that economic agents interact with an underlying motivation to imitate others.

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[2] In Durlauf's (1996) model, they create incentives for wealthier families to segregate themselves into economically homogeneous neighborhoods. The dynamics of these combinations explain persistent income inequality.

[3] An important class of poverty traps is due to coordination failures. Many such models are discussed in Cooper and John (1998) and Hoff (2001).

Since, an economic agent imitates his or her neighbors, given a particular state of the economy comprising different types of agents (high- and low-profile), firms and workers could imitate high-profiles engaging in R&D and human capital activities, because imitation is profitable and because there are strategic complementarities between the types of agents. Barret and Swallow (2006) show that when there are multiple strategies in dynamic equilibrium, it implies that poverty traps may arise. Since choosing a strategy means that one implicitly selects the equilibrium towards which one naturally moves over time, given the state of the system, such a strategy is a steady state of a dynamical system.

Therefore, we intend to study the dynamic complementarities and the evolution of an economy composed of different types of economic agents interacting within the constraints of such complementarities and the economic states that obtain.

We have chosen an evolutionary game theoretical model to analyze the above phenomena. Let us continue, in order to explain the advantage of the chosen approach.

1.1. Learning by Imitation

Blackmore (1999) pointed out not only how effective a form of learning imitation is, but also the sophistication required in order to be able to imitate. To explain why agents imitate, we should think of it as a kind of rational behavior. Rational imitation can be explained as follows. An agent, A, can be said to imitate the behavior of another agent, B, when observation of the behavior of B affects A in such a way that A's subsequent behavior becomes more similar to the observed behavior of B. An agent can be said to act rationally when the agent, when faced with a choice between different courses of actions, chooses the course which is the best with respect to her interests, her beliefs about possible action opportunities, and the effects of these potential action opportunities (for a survey on the notion of imitation, see Sanditov, 2006).

Durlauf (2001) noted that the imitative behavior may be due to:

1) psychological factors, an intrinsic desire to behave like certain others;
2) interdependence in the constraints that agents face, so that the costs of a given behavior depend on whether others do the same, or;
3) interdependence in information transmission, so that the behavior of others alters the information about the effects of such behaviors available to a given agent.

Each of these types of imitative behavior implies that an agent, when assessing alternative behavioral choices, will find a given behavior relatively desirable if others have behaved or are behaving in the same way.

In this thesis, we deal with imitation that results in agents performing a spectrum of tasks “as others do”. We assume that occasionally, each agent in a finite population gets an impulse to revise her (pure) strategy choice. If these impulses arrive according to independent, identically distributed (i.i.d.) Poisson processes, then the probability of simultaneous impulses is zero, and the aggregate process is also a Poisson process. Moreover, the intensity of the aggregate process is just the sum of the intensities of the individual processes. If the population is large, then one may approximate the aggregate process by deterministic flows given by the expected values. There are two basic elements common to these models. The first is a specification of the time rate at which agents in the population review their strategy choice. This rate may depend on the current performance of the agent’s pure strategy and of other aspects of the current population state. The second element is a specification of the choice probabilities of a reviewing agent. The probability that *i-strategist* will switch to some pure strategy *j* may depend on the current performance of these strategies and other aspects of the current population state.

Björnerstedt and Weibull (1996) studied a number of such models, where those agents who revise may imitate other agents in their player-population, and show that a number of payoff-positive selection dynamics, including the replicator dynamics, may be so derived. In particular, if an agent’s revision rate is linearly decreasing in the expected payoff to her strategy (or to the agent’s latest payoff realization), then the intensity of each pure strategy’s Poisson process will be proportional to its population share, and the proportionality factor will be linearly decreasing in its expected payoff. If every revising agent selects her future strategy by imitating a randomly drawn agent in their own player population, then the resulting flow approximation is again the replicator dynamics.

Theoretical advances to understand imitation have been developed by Vega-Redondo (1997) and Schlag (1998, 1999).[4] These two previously

[4]Schlag (1998) analyses the imitation rules that an agent should choose, when she occasionally has the opportunity to imitate another agent in the same set of types of players – which I refer to as a player-position – but is otherwise constrained by severe restrictions on information and memory. Schlag finds that if an agent wants a learning rule that leads to non-decreasing expected payoffs over time in all stationary environments, then the agent should (i) always imitate (not experiment) when changing strategy, (ii) never imitate an agent whose payoff realization was

cited works point out how an agent who faces repeated choice problems will imitate others who obtained high payoffs. Despite their basic similarities, these two models differ along at least two dimensions: 1) the informational structure (whom agents imitate) and, 2) the behavioral rule (how agents imitate). While agents in Vega-Redondo's model observe their immediate competitors, in Schlag's model, agents observe others who are just like them, but play in different groups against different opponents. Additionally, agents in Vega-Redondo's model copy the most successful action of the previous period whenever they can. In contrast, Schlag's agents only imitate in a probabilistic fashion and the probability with which they imitate is proportional to the observed difference in payoffs between their own and the most successful action. Apesteguia et al. (2007) show that the different results between the two models occur because of the different informational assumptions rather than the different adjustment rules.

So, whom an agent imitates is more important than how an agent imitates, and in this thesis we confirm this affirmation.

Now, we proceed to explain the notion that we have in mind about high-profile economic agents and the importance of the complementarities between those agents.

1.2. High Profile Economic Agents

The notion of strategic complementarities is widely studied and well understood, and thus the complementarity between R&D (innovative firms) and human capital accumulation (high-skilled workers) is widely accepted as an engine of economic growth (see the seminal paper by Lucas, 1988, or Mankiw et al., 1992; Stockey, 1991). In this thesis, we therefore label innovative firms and high-skilled workers as "high-profile economic agents" and they are the engine driving towards a high level equilibrium.

Nelson and Phelps (1966) and Schultz (1975) pointed out that the major role of education is to adapt to, and to generate, new technologies; that is, to adapt to technological changes generated by innovative firms. Modeling the idea, Nelson and Phelps (1966) assert that the major role of education is, first, to increase the agent's capacity to innovate, and second, to adapt to new technologies, thereby accelerating technological diffusion through the economy. Therefore, high-profile economic agents lead the

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worse than her own, and (iii) imitate agents whose payoff realizations are better than her own with a probability that is proportional to this payoff difference.

economy to a high-level equilibrium.

Redding (1996) formalizes this idea using an R&D-based growth model developed by Aghion and Howitt (1999). He shows strategic complementarities between investment in education and firms' investment in R&D, and then demonstrates the development trap when both types of investment are inactive. More recent studies develop different models to prove that high-skilled labor and high-technological firms are complements in order to obtain a high-level equilibrium (particularly, see Acemoglu, 1997; 1998). Acemoglu (1997) considers the same type of interdependence under heterogeneous individuals' human capital. Acemoglu (1998) focuses on skill-biased technological progress and inequality growth between and within groups of skilled and unskilled workers, focusing on common situations in which workers accumulate general skills to prepare for the obsolescence of their technology (firm-) specific skills due to technological progress.

In fact, it is generally thought that new technologies reduce the demand for low-skilled workers and increase the demand for high-skilled workers, since high-skilled workers adapt more easily to technological change.[5] This is the well-known notion of "Skill-Biased Technical Change" which implies a shift in the production technology that favors high-skilled over low-skilled labor by increasing its relative productivity and, therefore, its relative demand (see Acemoglu, 2002; Aghion, 2006; Hornstein et al., 2005).

Following this, a number of recent contributors have emphasized the role of skill resources as a crucial constraint on the selection of the technological profile to be implemented in an underdeveloped economy. Hendricks (2000) develops a model of growth through technology adoption focusing on the complementariness between technologies and skills. The workers' skills and the technological profile of firms are complementary because the level of available skills limits the profile of technologies that firms can use, while the technological profile determines the rate of learning. By focusing on the role of human capital in economic development, Benhabib and Spiegel (1994) suggest that the specific role of the human is to facilitate the adoption of technology from abroad and to create domestic technology. This evidence reinforces the importance of the matching between skills and technological profiles. In this sense, Lavezzi (2006) focused on the dynamics of human capital accumulation (by means of a Markov chain) where human capital accumulation and technology

[5]This assumption is akin to the Nelson and Phelps' (1966) argument that greater skills allow for faster adoption of technology.

adoption are interrelated processes. According to him, matching is fundamental in order to isolate one of the most important aspects of the acquisition of human capital and technology. For workers, the crucial issue is the type of firms they interact with, while for firms, it is the type of workers they hire. In the high-skill equilibrium, for example, workers expect firms to invest in technology and then invest in human capital. Given these workers' expectations, firms find it optimal to invest, and therefore expectations are fulfilled in equilibrium.

Some empirical research for Latin American countries (LAC) has been conducted by Cimoli et al. (2009), who point out that the accumulation of human capacities, technological capabilities and the specialization of the production structure shape the response and the way to overcome low level equilibria in LAC. For instance, the Latin American evidence shows a mismatch between the complementarities of innovation and human capital, e.g. the case of the so-called *maquiladoras* in the north of Mexico and low-skilled workers (see Kopinak, 1995),[6] where Mexican labor is inexpensive, and, courtesy of NAFTA (the North American Free Trade Agreement), taxes and custom fees are almost nonexistent, which benefit the profits of corporations. The 'maquiladorized' industry paid lower wages, was non-union in orientation, classified most workers as low-skilled, and was characterized by a high proportion of women workers. An article in *Ward's Automotive Reports* (1997) indicates that the technology mix in Mexican automotive assembly plants is different to that in U.S. assembly plants to take advantage of lower labor costs in Mexico. These lower labor costs reflect the lower productivity of Mexican workers, which itself reflects (presumably) lower levels of human capital. Hence, the type of automotive plant chosen depends, to an important extent, on the skill composition of the workforce. Presumably, the development or adoption of many technologies reflects the supply of factors complementary to the technology. After all, there is no point in developing a capital good that requires skill levels that exceed those of your workers.

Santiago-Rodriguez and Alcorta (2006) investigate the role of human resource management and development practices underpinning firms' performance and innovation in Mexico. The authors critically addressed some of the main challenges and attributes that one may need to take into account to design and eventually implement a study about the nature of links between human resource management practices and firms' performance in innovation.

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[6] *Maquiladoras* are export assembly plants in northern Mexico, producing parts and products for the United States.

In a similar vein, Maloney and Perry (2005) studied the LAC and the high tech miracles have followed very different recipes for R&D, FDI, licensing, and education. They show that Latin America has followed a recipe that has relied little on R&D or licensing and too heavily on FDI. This is perhaps a worrying finding given the low rates of technological transfer with FDI, and it appears especially worrying given the generally passive approach to taking advantage of the technological benefits of FDI. In Mexico, for example, despite the presence of IBM and HP, which have been in Guadalajara for 30 years, there is little evidence of a knowledge cluster in computer technologies, at least as captured by patenting data (see Maloney and Perry, 2005).

On the other hand, Argentina and Uruguay are good examples of countries that have accumulated human capital (people with high-levels of education), but with low-levels of advanced technology. Ros (2000) pointed out that Latin American countries are paradigmatic cases of the need for further conditions of a process of sustained growth. Most of them, even with very high initial levels of formal education, did not grow as fast as other countries that started with similar initial levels of human capital.

Further interesting research was conducted by Vonortas (2002) who empirically assessed science, technology, and innovation policy initiatives in Latin American countries. He found that R&D expenditures remain low, with international standards ranging from approximately 1% of GDP for Brazil, to 0.75% for Chile, 0.5% for Mexico, and 0.3% for Argentina. Moreover, their distribution was biased towards governments and universities and against the private sector. Encouraging the private sector to innovate, and particularly the vast majority of small and medium sized enterprises that dominate economic activity, has proven a long and arduous task. Vonortas offers examples from two of the largest and most advanced countries in the region (Brazil and Mexico), a medium-sized, high-growth, relatively advanced country (Chile), a smaller-sized developing country with significant pockets of economic activity (Panama), and three smaller-sized, developing countries (Honduras, Jamaica and Nicaragua).

In any case, in this thesis, we do not want to enter into the debate surrounding, for example, how to conduct R&D, FDI and innovation policy initiatives. The purpose of this thesis is going to be clarified in the next sections, but as we have mentioned, our aim is to study the dynamic complementarities and the evolution of an economy composed of different types of economic agents interacting within the constraints of such complementarities and the economic states that obtain.

1.3. Strategic Behavior of Economic Agents

We argue that the empirical evidence about the mismatch between the complementarities of innovation and human capital can be explained by the strategic behavior of firms and workers, both of which must decide whether or not to invest in R&D and human capital given the current state of the economy. The current state of the economy means the profile or distribution of different types of economic agents, i.e. the current distribution of high and low profile economic agents, which represents the profiles of firms and workers.

The strategic behavior can be explained as follows.

Assume that potential workers imitate their neighbors; that is, they decide to be high or low profile economic agents. Specifically, they decide whether to be a high-skilled worker (e.g, more educated, more able, more experienced) by going to a training school, or to be a low-skilled worker who doesn't incur the costs of training. Such decisions are rational in the sense that they imitate the best performing strategy given the current state of the economy. On the other hand, firms' decisions depend on the composition of labor in the economy. That is, if the number of high-skilled workers is large enough, then a firm decides to be an innovative firm and invests in R&D, otherwise a firm decides to be non-innovative and does not invest in R&D.

Assume that you are a potential worker. First, you need to decide whether to study (say a degree in mathematics or economics or chemistry) or not, and then to enter the labor market and to supply your labor. If you decide to study, then you will be a high-skilled worker, whereas if you decide not to study, you will be a low-skilled worker. The latter scenario currently occurs in most developing countries, where many young people seemingly prefer not to spend more time studying in order to enter the labor market immediately and to offer whatever services they can in order to start receiving a wage, since they observe that a mathematician or chemist or economist is likely to be unemployed. If your decision is taken according to an imitation rule – that is, if you can observe that your neighbors are earning more when they enter the labor market without specializing – then you will imitate them and you will decide not to study. But the converse will happen if you observe that your neighbors are specializing and then are supplying high-skilled labor which gives the maximum expected payoff. In any case, the decisions of potential workers whether to become qualified or not (training or no training) depends on the probability of being hired by innovative and non-innovative firms; that is, it depends on the complementarity between R&D and human capital. At the same time, firms decide to invest in R&D departments just when it is profitable and they base this decision on having a certain number of high-skilled workers to harness new technologies. But if the local economy is highly composed of low-skilled labor, then firms decide not to invest in R&D departments and they may import the necessary technology to produce and to compete.

Hence, we aim to analyze what is likely to occur in developing countries where the population of firms and workers are characterized by a mismatch of high and low profile economic agents, i.e., a mismatch of innovative and non-innovative firms with high-skilled and low-skilled workers.

1.4. Outline

The rest of this book is composed as follows. Chapter 2 summarizes the main notions of evolutionary game theory such as: population games, evolutionarily stable strategies (ESS), the ESS against the field, the replicator dynamics, and the relationships between evolutionarily stable strategies and the steady states of the replicator dynamic system. Moreover, we present the notion of a behavioral rule as a crucial concept of the individuals' behavior.

Chapter 3 studies an evolutionary game of two asymmetric populations where, in each round, a player in population 1 is paired with a member of population 2. We present two imitation models. In the first model, dissatisfaction drives imitation. In the second model, agents imitate the successful. In the first model, we use a simple reviewing rule, while in the second model, we use a proportional imitation rule where switching depends on agents comparing their payoffs to others' payoffs. We show that such imitative behavior can be approximated by a replicator dynamic system. We characterize the evolutionarily stable strategies for a two asymmetric populations normal form game and we show that a mixed strategy is evolutionarily stable if and only if it is a strict Nash equilibrium. In addition, we characterize the evolutionarily stable strategies of our model. Moreover, we extended the model to the application of a specific behavioral rule where a reviewing strategist, *i*, who decides to change her current strategy must consider the probability to imitate a strategy that performs better than her current strategy and the probability of meeting the agent who uses such a strategy. From this investigation, we offer one clear conclusion: whom an agent imitates is more important than how an agent imitates.

Chapter 4 develops an evolutionary coordination game of signaling by economic agents, such that the agents' rational behavior may result in a poverty trap. We argue that poverty traps exist and occur because of strategic complementarities between profiles of agents (for example: low-skilled workers, no innovative firms, and scarcity of human capital and R&D). First, we introduce a coordination game between "leaders" and "followers" with different profiles. Second, we study the game as an evolutionary game of complementarity between the profiles of economic agents. We find the self-confirming equilibria and the ESSs against the field. We conclude that the possibility of either high-level or low-level equilibria implies that economic agents acting under identical settings may experience either an adequate living standard or deprivation (growth or crisis), and this depends only on the initial conditions. Then, if the current state of the economy is composed mainly of low-profile economic agents, the economy converges to a low-level equilibrium since it is rational for every player to imitate those strategists with low-profiles. But if the state of the economy changes and there is a sufficiently high number of high-profile agents, then players imitate those agents with high-profiles, and the economy converges to a high-level equilibrium.

Chapter 5 considers a model where workers' decisions are driven by imitative behavior and firms' decisions depend on the number of high-skilled workers. We analyze the dynamic complementarities between innovative firms and high-skilled workers. We show that when firms invest in R&D in order to become an innovative firm, they are successful only with the presence of a sufficiently high number of high-skilled workers (as in Redding, 1996). At the same time, workers are encouraged to increase their skills when a large number of firms make investments in high technology. Conversely, firms that do not invest in R&D, do not look for high-skilled workers, and therefore make the accumulation of skills unprofitable. We show that there exists a threshold number of innovative firms above which it becomes advantageous to accumulate human capital or high-skilled workers. This is the mechanism that allows an economy to move beyond the poverty trap. Then, we show that if, in a given economy, the percentage of innovative firms is under a certain threshold value, then the economy evolves to a poverty trap where the number of high-skilled workers decreases to zero, and thus it becomes better for firms not to invest in R&D. But we also show that if the initial percentage of innovative firms is higher than the threshold value, then, where workers are following an imitation rule, the economy will evolve to a high level equilibrium. In fact, the high level equilibrium is a steady state of a dynamical system characterized by the fact that a percentage of non-innovative firms coexist with a percentage of innovative firms and a percentage of high-skilled workers coexist with a percentage of low-skilled workers. This result shows the real experience of many developing countries in which there is a mismatch between investment in R&D and Human Capital accumulation, which are the engines of sustained economic growth.

Moreover, the low level (dynamic) equilibrium (the poverty trap) corresponds with a Pareto dominated Nash equilibrium of a two population normal form game, while not one of the possible high level (dynamic) equilibria correspond to the Pareto dominant equilibrium of this game.

Chapter 6 studies the evolution of firms and workers by replicator dynamics. The aim is to extract the evolutionary dynamics from the replicator dynamic system, when the decisions of both firms and workers are driven by imitation. Moreover, we consider payoff taxations and subsidies to achieve the replicator dynamic system where the *target population state* has overcome the poverty trap.

Hence, we characterize the steady states, the ESSs, and the threshold values required to move from low level to high level equilibrium.

We conclude that the imitative behavior of the economic agents can explain the evolution of the economy toward high or low equilibria. Then, if being a high-profile economic agent is the successful strategy because the current state of the economy encourages you to raise your profiles, then imitation facilitates the choice of education (or human capital accumulation), and firms in turn decide to invest in R&D. The crucial parameters that encourage agents to become high-profile are education costs (training costs), skill premia and income tax as a policy to incentivize investment in R&D.