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Environmental policy and technology diffusion under imperfect competition

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Chapter 2

Evolutionary game theory

2.1 Introduction

This chapter discusses the theory of evolutionary games. It will be addressed why an evolutionary approach is especially useful to analyze the problems outlined in the previous chapter. But before doing this, we first need to determine carefully what evolutionary game theory embodies. How is it defined, what are its main features and what are the main differences with classic game theory? In short, what does evolutionary game theory add to conventional economic (game) theory?

We first examine its field of origin, namely that of evolutionary biology. Evolutionary game theory originated as a *methodological* branch of the biological science. In order to make the way of thinking more substantial, we will depart from a somewhat broader perspective and first take a look at the relationship between economics and biology from a general point of view. This will be done in section 2.2. In Section 2.3 and 2.4, the method of evolutionary game theory in both biology and economics will be discussed respectively. Section 2.5 evaluates the main features of evolutionary game theory. In section 2.6, we explore in a qualitative way how the framework of evolutionary game theory applies to Cournot markets and technology diffusion. Section 2.7 finalizes the chapter with concluding remarks.

2.2 Economics and biology

Economics and biology have certain features in common and there have been interactions. Work of economists have inspired biologists and methods developed by biologists have been adopted by economists. Although the scientific approaches, such as the assumption of optimizing behavior in economics and natural selection in biology, seem totally different at first sight, a closer look reveals striking resemblances. We shall elaborate on this issue in this section and prepare the ground for the exposition of evolutionary game theory and its application to biology (section 2.3) and economics (section 2.4).

2.2.1 Processes and relationships

Elements that play a key role in evolutionary biology are natural selection and evolution. Evolution, defined by Wilson (1975) as *any gradual change*, is basically driven by the force of natural selection, or more generally, selection. Selection is defined as the change in the relative frequency in genotypes due to differences in the ability of their phenotypes to obtain representation in the next generation (Wilson, 1975, p.67). Selection and evolution are concepts inherited basically from Darwin's path breaking *On the Origin of Species* (Darwin, 1859). In this classic, Darwin advanced the issues of evolution and natural selection. Although Darwin was inspired by Malthus' economic theory of human population growth, it is only quite recently that economists recognize the importance of these concepts with respect to the implications for human behavior (e.g. Waldman, 1994).

When evolutionary concepts also play a role in other scientific disciplines, one talks about so-called 'biological analogies'. Given the economic orientation of this thesis, we concentrate on the economic discipline as such. The New Palgrave (Eatwell *et al.*, 1987) includes the following phrase about biological analogies:

> To the extent that biology 'owns' the concepts of natural selection and evolution, the meanings of these terms tend to be regarded as biology-specific. It then seems to follow that the application of evolutionary thinking in other realms falls under the rubric 'biological analogies', whence it is believed to follow, further, that the appropriateness of an evolutionary approach somehow depends on the closeness of the parallels that can be drawn between the situation in view and situations considered in biology (The New Palgrave, 1987, vol. 3, p.614).

Biological analogies in economics also exist and go even back as far as the period of Thomas Robert Malthus. It refers to the connection between Darwin's notion of survival of the fittest, based on principles of evolutionary selection, and economics. Malthus' main point was that, in the end, a growing population would be restricted in its size by the limits set by the available natural resources, in particular arable land for food production. The mechanism which induced the stagnation of population growth, was a declining standard of living and in the worst case starvation and war. No human remedy could stop the working of the natural law adjusting population size with respect to its natural resource base. Therefore, Malthus was not in favor of poor relief since it would ultimately stimulate population growth and thus aggravate social problems. If people were unable to practice the moral constraints, the only solution essentially came down to letting the forces of evolutionary selection in terms of high mortality among young children, diseases and, occasionally, famine do the work.

In the late nineteenth century, Alfred Marshall (1891) also recognized the importance of evolutionary features for an economic analysis. Actually, according to Marshall economics is a branch of biology. In the eyes of Marshall, the social sciences is a subdivision of sociobiology (e.g. Hirshleifer, 1977). This because the subject of biology, or more specifically sociobiology, is defined as the systematic study of the biological basis of *all* social behavior (Wilson, 1975, p.4).

The basic parallel that can be drawn is that both economics (as part of the social sciences) and sociobiology analyze the adaptive behavior of living creatures. Both disciplines share the studying of behavior of actors and survival of actors (behavior) in an external environment marked by competitive pressures. A simple intuitive example shows the common processes of and relationships between economics and sociobiology. For instance, in biology one could think of a species that is trying to survive, facing threats of food scarcity, territory demarcation and possibly the existence of predators. In case of economics, one could think of a market in which a firm is trying to survive given the (strategic) behavior of competitors and, for example, the implementation of government policies. In both cases, Darwin's notion of survival of the fittest is present. Hirshleifer (1977) provides a comprehensive overview of the various processes and relationships. Table 2.1 provides a summary of this.

The basic postulate in economics is utility maximization. Humans, firms and governments all try to maximize their corresponding preferences. The biological counterpart is that as many genes or animals of a certain species will be reproduced in subsequent generations in order to maintain their survival in the long-run. This is called reproductive survival[1]. How do the two scientific fields

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[1] Reproduction is synonymous with the term *replication* which was first introduced by Richard Dawkins (1976).

Table 2.1: *Processes and relationships (Source: Hirshleifer, 1977).*

	Economic system	Biological system
Objective function:	Subjective preferences	Reproductive survival
Principle of action:	Optimization (satisficing)	'As-if' optimization
Opportunities:	Production	Resource exploitation
	Exchange via market	Mutualism
	Crime, war	Predation, war
	Family formation	Reproduction
Competitive selection:	Economic efficiency	Superior fitness
Equilibrium:		
short-run	Market clearing	?
long-run	Zero-profit	Reproductive ratio = 1
very long-run	Stationary state	Saturated environment
Progress:	Accumulation,	Evolution
	Technological advance	
	Institutional change	

determine the optimal strategy for meeting the corresponding objective function? The economic discipline makes use of optimization techniques. Unlike economics, in biological applications it is unrealistic to presume the ability of an animal or gene to reproduce itself, based on conscious maximization. However, biological theory shows that only those animals (or genes) that adapt best to changes in their 'social' and natural environment will survive in the long-run. That is, survival of the fittest is conceived in a way *as-if* they were maximizing their objective function, given the constraints set by their natural environment. We shall elaborate on the *as-if* paradigm in the next section.

To maintain survival of preferences and reproduction the economic and biological systems have different opportunities. In economics one could think of manufacturing goods or generating services and subsequently exchanging these goods and services on the market. Other economic opportunities are war (recall Malthus' argument above), crime and family formation. In biology reproductive survival could be secured by means of resource exploitation, mutualism[2], predation, war and reproduction.

The success of exploiting the opportunities is measured in terms of efficiency and superior fitness in an economic and biological sense respectively. For instance, in the long-run a firm will not survive the market when a sufficiently large number of competitors are more efficient, i.e., the latter simply outperform the less efficient firms. The biological analogy of economic efficiency could be that behavioral fitness of a particular organism is superior relative to its direct competitors. The process through which this is channeled is the force of inheritance. While economic efficiency and superior fitness are analogues, Hirshleifer (1977) points out that competition processes in biology and economics are less comparable and to him it is not clear what the economic parallel of the inheritance process is. We want to add here that imitation of successful behavior could be the mechanism through which the adjustment process works. We shall come back to this in subsection 2.2.2.

Selection implies dynamics. Given the dynamics of competition, a natural question is to what state or equilibrium the system will converge. The economic approach makes a distinction between the short-run, long-run and the very long-run. The condition for equilibrium in the short-run is simply the equalization of quantities demanded and supplied, i.e., market clearing. The long-run state coincides with the zero-profit condition defined by entry and exit: firms will enter the market when profits are positive and the process continues until profits are zero and no incentive for entering exists anymore. One can add here that elimination of inefficient firms is the other aspect of long-run adjustment. A final distinction of equilibrium states is the one established in the very long-run, referred to as a stationary state.

According to Hirshleifer, there seems to be no close analogy in biology to the short-run concept of economic science. He puts forth that

> [..] the equivalent of the long-run equilibrium condition can be taken to be the biological situation where each type of population (on the organism level) or each type of allele (on the genetic level) has a reproductive ratio equal to unity. And one can also imagine a hypothetical very long-run equilibrium condition in which the environment is so totally saturated as to leave no niche for the formation of new life entities (Hirshleifer, 1977, p.51).

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[2] Mutualism is the interaction between two (or more) species that is beneficial to both (all).

Finally, an analogy between economics and biology for the characterization of progress can be made. The biological term for progress is simply evolution. Hirshleifer (1977) comprises this as the improvement of adaptation to the environment by a variety of processes. In economics, progress appears in terms of resource accumulation and technological advance. In addition to these elements singled out by Hirshleifer, one has to mention the adjustments in the organization of economic life. In particular, Hayek (1979, 1988) has pictured the market system as an evolutionary process over centennia in which more efficient adjustments survived and less efficient organizational changes were abandoned. Therefore, Hayek presents the market economy as the result of human *action* rather than human *design*.

Given the preceding outline of processes and relationships, the following quote summarizes the isomorphic relationship between biology and economics:

> [..] the isomorphism between economics and sociobiology involves the intertwining of two levels of analysis. On the first level, acting units or entities choose strategies or develop techniques that promote success in the struggle or competition for advantage in given environments [..] The second, higher level of analysis examines the social or aggregate resultant of the interaction of the striving units or agents [..] The pursuit of advantage on the part of acting units takes place subject to opportunities and constraints that emerge from the social context, while the resulting social configuration depends in turn upon the strategies employed by the advantage-seeking entities (Hirshleifer, 1977, p.2).

As we shall see later, this is exactly what is important within an evolutionary game context. Now we have examined some parallel concepts, we will turn our attention towards game theory as a framework for analysis. With respect to game theory, one of the main issues is related to the assumptions headed as 'principle of action' in table 2.1, viz. optimization and *as-if* optimization, i.e., natural selection. The two principles of action somehow reflect the adaptive processes that are endowed in economical and biological systems. More precisely, where both economics and biology share as focal point the analysis of adaptive processes, it is basically in terms of *methodology* or *approach* in which they differ. We will elaborate on the two action principles of optimization and *as-if* optimization in the following section.

2.2.2 Natural selection versus optimization

The basic premise of neoclassical economic theory is that economic subjects optimize behavior. This assumption also applies to classical game theory. To optimize a certain objective function, the players are assumed to be unboundedly rational, translated in assumptions of perfect information and unlimited capacities to calculate all possible options given the behavior of all the other players involved in the game. In short, the economic actor is characterized as an omniscient hyperrational entity.

These neoclassical optimization postulates have met the critique that, in real life, players do not have perfect information and rather face limited calculating capacities. So, economic agents basically act in a boundedly rational manner (e.g. Simon, 1957). In this regard, one could think of actors following so-called rules of thumb in guiding their behavior rather than applying optimization techniques to each decision they make. In the spirit of Herbert Simon's seminal work, Cyert and March (1963), Winter (1971) and Nelson and Winter (1973, 1982) use this type of methodology by emphasizing firm routines and decision rules based on satisficing behavior. This is often referred to as a *behavioral approach*. A behavioral approach could be applied to any economic subject, but given the purpose of this dissertation, we stick to the firm as the relevant economic entity.

Evolutionary selection principles could serve as the main attribute for a behavioral approach. The arising issue here is whether under competitive pressures, firms that do not perform well against other firms in the industry, will be wiped out in the long-run. In this case, profits could serve as a natural basis for selection since firms must make positive profits in order to survive, invariant of whether they do this consciously or not (Alchian, 1950). The evolutionary process shows that, eventually, only firms with non-negative profits survive. Alchian especially mentions imitation as a basis for firm behavior. In the light of uncertainty, i.e., bounded rationality, firms do not know exactly how to make the highest profits and so other similar fashioned firms that are successful will be the source for imitation. The evolutionary selection principle in terms of imitation transmits the successful imitations to other firms. Imitation thus replaces inheritance as a mechanism of natural selection.

In the same vein goes the argument by Milton Friedman (1953). He postulates that, to a large extent, evolutionary selection coincides with optimization. Due to competitive forces, selection will favor behavior that eventually results in the survival of those economic actors which exhibit optimal behavior, i.e., behavior based on optimization postulates. For example, taking firms as the acting economic subject, Friedman (1953, p.18) states that: 'under a wide range of circumstances individual firms act *as-if* they were seeking rationally to maximize their expected returns [..]'. Call this the 'evolutionary hypothesis'. With respect to this hypothesis he continues (p.19): 'The process of natural selection thus helps to validate the hypothesis - or rather, given natural selection, acceptance of the hypothesis can be based largely on the judgement that it summarizes appropriately the conditions for survival.' The *as-if* postulate represents selection by market forces.

This thesis deals with imperfect competition and features strategic interaction among firms. A way of modelling this is by game theory. Incorporating the *as-if* maxim makes game theory by definition evolutionary. The question arises what the implications of natural selection, viz. *as-if* optimization, for classical game theory are. Since evolutionary game theory finds its roots in the biological science, we will start the discussion from there and subsequently enter the field of evolutionary game theory for modelling economic phenomena.

2.3 Evolutionary games in biology

Now we have provided a general overview of the intertwining between economics and biology, the next step is to focus on the methodology of evolutionary game theory. The original evolutionary game theoretical framework stems from biology and the terminology makes a clear linkage with the theory of biological evolution. In the early 1970s, a seminal article of Maynard Smith and Price (1973) appeared in the leading journal *Nature*, which ignited the further development of evolutionary game theory. Another classic is Maynard Smith (1982), in which the previous work of Maynard Smith and Price (1973) and Maynard Smith (1974) is outlined and extended. The essence of their contribution is the development of the static equilibrium concept called 'evolutionary stable strategy', and which can be seen as a Nash equilibrium refinement. The different equilibrium notions will be addressed more thoroughly in subsection 2.3.4.

Maynard Smith and Price were, in fact, not the first who applied game theoretical concepts to biology. The actual starting point is Lewontin (1961). He investigated the extinction of species by seeking strategies (behavior) that minimized the probability of extinction. The species in his study were playing a so-called Game Against Nature (GAN). In such a game, players[3] take current

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[3] In Lewontin's case the players are the individual members of a population of a species under consideration.

and future behavior of the other players as given. As we shall see in section 2.4, the GAN condition is also essential for economic or social oriented applications. Before the economic oriented part will be discussed, we first examine the main features of evolutionary games from a biological point of view. Once we know the fundamentals in a biological sense, the transition to the applied economics part may become more transparent.

Another forerunner of Maynard Smith and Price (1973) and Maynard Smith (1974, 1982) is Hamilton (1967). He developed an equilibrium concept called 'unbeatable strategy', which is basically equivalent to the concept of evolutionary stable strategy. We now turn to the characterization of evolutionary game theory by formally defining it and reviewing its basic assumptions, again within a biological setting.

2.3.1 Definition, essence and assumptions

What is evolutionary game theory? Within biological boundaries, evolutionary game theory is a way of thinking about evolution at the phenotypic level when the fitness of particular phenotypes depend on their frequencies in the population (Maynard Smith, 1982, p.1). In biology, the population consists of organisms. The visible form of a characteristic (trait) of an organism is called phenotype. It thus represents anything that is part of the observable structure, function or behavior of organisms. For instance, these can refer to molecules, cells, energy utilization, organs or reflexes and behaviors (Blamire, 2000). In economic games the key trait usually is the behavior channeled through strategies that individuals of the population have at their disposal. Therefore, from now on we shall use the term strategy, but remind that in biology the terms 'strategy' and 'behavioral phenotype' are interchangeable.

In an evolutionary game one talks about fitness, representing Darwin's notion of 'survival of the fittest'. Obviously, the players in a population are not humans but are often represented by a certain species or genes. Subsequently, in biology it is assumed that these type of players do not consciously choose a certain type of action, but rather can be seen to be pre-programmed to activate some strategy. The fitness of a strategy is the outcome assigned to a particular strategy followed by some entity (given the current behavior in the population). Consider for instance a biological model where the entity is a certain gene. The strategy of the gene is to transfer a particular phenotype to another organism. In this type of model the fitness criterion is often the number of offspring of the particular gene.

Given the current distribution or spreading of behavior in the population, the strategies that are 'fit', i.e., that do well against other strategies within the population, have a tendency to grow relative to the less fit strategies. The fitness of a strategy depends on how many players currently are endowed with this gene. This idea of *frequency-dependent selection* is the essence of an evolutionary game. The emphasis is on the behavior of the population as a *whole* rather than the individual player, but the methodology gives room for analyzing both levels simultaneously[4]. So, evolutionary game theory is a tool to describe the evolution of strategies under the pressure of natural selection.

The theory basically relies upon two assumptions, namely a large uniform population of players and random bilateral matching. First, the large uniform population assumption. The obvious question is: when can the size of a population of a certain species or genes be regarded as 'large'? In the theoretical biological literature, often an infinite number of individuals is considered. In turn, the weight of a single individual is very low given the large size of the population, which is related to the payoff structure. As Vega-Redondo (1996, p.11) states: 'That is, a context where the influence of the population on the payoff of any given individual is contained in the anonymous description of the frequencies with which each strategy is being played by the population'. We will see in section 2.4 that this argument is also important in an economic context. A second and technical reason for focusing on a large population is that by applying the 'law of large numbers', one can easily calculate the expected payoff and use this as an approximation for real actual payoff.

Second, given the large population size, individuals are drawn randomly from the population and are matched to play a pairwise repeated game. The implication of this assumption is that there is no account for local interaction. Every player has an equal chance of being matched with another player. Later biological studies (e.g. Hamilton, 1967) explore a less restrictive version by allowing local interaction. The reason for this is that situations are present in which animals compete for food in the same habitat or local natural area in which they live. The chance of meeting another member in an adjacent neighborhood is then simply higher than the probability of meeting a member of the population outside this area. So, evolutionary games in their basic form do not consider differentiation to location or region.

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[4] Recall Hirshleifer's phrase in subsection 2.2.1.

2.3.2 Basic model elements

Before discussing the elements of an evolutionary game model qualitatively, we will introduce the mathematical equivalent of the various elements. We basically adopt the framework developed by Daniel Friedman (1991, 1998). Table 2.2 encloses the elements that are essential for an evolutionary game model.

Table 2.2: *Evolutionary game elements.*

Element	Denotation
Number of populations:	$k = 1, \dots, K$
Number of players in population k:	N_k
Number of strategies for player $i \in N_k$:	$j_k = 1, \dots, J_k$
State space:	s_k
Payoff (fitness) function:	$g_k(j_k, s_k)$
Selection dynamic:	$\dot{s} = \begin{pmatrix} \dot{s}_1 \\ \vdots \\ \dot{s}_K \end{pmatrix},$
	with $\dot{s}_k = \begin{pmatrix} \dot{s}_{1,k} \\ \vdots \\ \dot{s}_{J,k} \end{pmatrix} = \begin{pmatrix} \frac{ds_{1,k}}{dt} \\ \vdots \\ \frac{ds_{J,k}}{dt} \end{pmatrix}$
Equilibrium concept:	NE, ESS, EE

A first element is a set of distinct populations $k \geq 1$. Recall that the basic evolutionary game model in biology postulates one large uniform population of players. Contrary to this, Friedman's framework allows for more than a single homogeneous population. To get somewhat ahead on the economic discussion of the evolutionary game modelling, one could think of a situation with, for instance, two interacting populations. For example, one population of sellers of a particular commodity and one population consisting of buyers[5]. However, since the diffusion model to be developed in this thesis is one-dimensional (one industry is considered), we will from now on only examine this case.

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[5] See Friedman (1991) for a discussion of such an example.

Next to the number of populations, each population k consists of a number of individuals denoted by N_k. Every population thus can have a different number of players. Furthermore, each player $i \in N_k$ can choose a strategy j from a finite set of strategies that it has at its disposal: $j_k = 1, \ldots, J_k$. This implies that within the populations, different groups (or subpopulations) can be distinguished playing a specific strategy. The relative number of shares in population k playing strategy j is represented by the state space s_k. So, in an evolutionary game the state usually reflects the distribution of strategies across the population.

A game played in a certain population k yields payoffs according to a fitness (payoff) function $g_k(j_k, s_k)$, which is contingent on the strategy choice j_k and current state s_k. In particular, the fitness function g_k generates the payoff of strategy j_k when played against the population's current strategy configuration s_k.

The change of the population level strategy distribution $\dot{s}_k$ is governed by a (selection) dynamic which describes how the state evolves over time, i.e., the distribution of strategies within population k. The selection dynamic can be of a deterministic or stochastic nature. Throughout this dissertation, we employ a deterministic continuous time dynamic for reasons of technicality and simplicity. This issue will be addressed below.

Finally, as a last element of the evolutionary game model, it has to be investigated whether the system will converge to a stable steady state. This implies the need of an equilibrium classification. One of the most influential equilibrium concepts is Nash equilibrium (NE). Moreover, some other (evolutionary) concepts were developed, viz. 'evolutionary stable strategy' (ESS) and 'evolutionary equilibrium' (EE).

The above shows that there is a narrow relationship between the payoff function, the dynamics and the final equilibrium concept. We will now elaborate on this relationship by discussing the dynamic structure (subsection 2.3.3) and equilibrium concepts (subsection 2.3.4).

2.3.3 Evolutionary dynamics

We are particularly interested in the long-run consequences of repeated short-run interactive decisions that are subject to a selection force. Moreover, it was argued that classic game theory heavily relies on strong and extreme forms of rationality of the interacting players. Given these strong assumptions, equilibrium concepts like Nash equilibrium and other non-cooperative equilibrium refinements were constructed. However, as Alchian (1950), Milton Friedman (1953) and Winter (1971) argued, when players do not meet the perfect rationality presumption, evolutionary selection of behaviors might yield long-run outcomes similar to the predictions of a theory assuming complete rationality, thus approaching the '*as-if*' maxim.

The selection force governing evolution is also referred to as an adjustment dynamic and represented by a dynamic system. Often, when selection is based upon principles of natural selection, one also uses the notion of 'evolutionary dynamics' or sometimes 'Darwinian dynamics'. An evolutionary adjustment dynamic captures the principle of better performing strategies growing relatively faster than the strategies that are doing worse. This principle is called monotonicity. Different specifications of monotonicity can be found in the literature, but all capture the idea of an increase in the adoption of higher payoff strategies relative to lower payoff strategies.

One of the prototypical evolutionary selection dynamics used in biological studies is the so-called replicator dynamic[6] (e.g. Hofbauer and Sigmund, 1988). The replicator dynamic, introduced by Taylor and Jonker (1978), describes the evolution of strategies in the entire population of organisms and assumes that strategies that perform above average, grow faster compared to the strategies that are doing worse than average. More precisely, the growth rate of a strategy equals the relative fitness of that particular strategy.

The interesting question linked to the dynamics is: to what steady state will the game possibly evolve? What is needed to answer this question is an equilibrium framework. We will therefore now examine the most relevant equilibrium concepts in evolutionary game theory.

2.3.4 Equilibrium concepts

The equilibrium concept central to economic theory is, undoubtedly, Nash equilibrium as developed by Nash (1950). Extracting the Nash equilibria from an economic model requires complete information for every player. Moreover, it is a static concept and is therefore useful for an analysis of a game that is not repeated over and over again. In addition to this, many economic or social problems often have multiple Nash equilibria and it then is hard to determine which equilibrium is more likely to be selected.

In this thesis we deal with a dynamic Cournot game and are especially inter-

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[6] Instead of the replicator dynamic, the literature may also use 'Malthusian dynamic' (e.g. Friedman, 1991).

ested in the long-run outcome of the system under a nonlinear payoff structure[7]. The industrial organization literature (e.g. Tirole, 1988) shows that the basis of a Cournot game is Nash equilibrium (in particular Cournot-Nash equilibrium) and so we will depart from there. Then the discussion focuses on the equilibrium refinements 'evolutionary stable strategy' (ESS) and 'evolutionary equilibrium' (EE). These two concepts play a key role in the evolutionary game literature and give better insights when the game is played under forces of natural selection and, for this reason, they are relevant for the analysis and discussion of our main problem. The Nash equilibrium, evolutionary stable strategy and evolutionary equilibrium definitions are based on the specification of the fitness function as given in table 2.2.

Nash equilibrium

A Nash equilibrium is a situation in which it does not pay off for a player to deviate from it. In other words: the strategy or action of each player is a best response to the opponents' strategy choice. For example, in case of a Cournot setting, a Nash equilibrium is that combination of outputs such that no firm can increase its profits by changing its output alone. Formally:

Definition 1 *A strategy (or state) $s \in S$ is a Nash equilibrium if for all $y \in S$: $g(y, s) \leq g(s, s)$.*

Here s is the current state of the system and S denotes the overall state space. What the definition says is that the current state s constitutes a Nash equilibrium whenever the payoff in a state y different from s is lower or equal to the payoff in the current state. Deviating from this state (or strategy) would generate a lower payoff and so no incentive exists for changing behavior in such a situation.

Evolutionary stable strategy

Based upon the concept of 'unbeatable strategy' introduced by Hamilton (1967), evolutionary biologists developed the equilibrium concept 'evolutionary stable strategy' (ESS), sometimes also referred to as 'evolutionary stable state' (Maynard Smith and Price, 1973; Maynard Smith, 1974). An evolutionary stable strategy is a stationary situation in the evolutionary process and defines a state of the population that is so-called 'uninvadable' by any mutant behavior of an

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[7] In evolutionary biology a situation of nonlinear payoffs is referred to as 'playing the field'.

arbitrarily small fraction of the population. Uninvadability of the state implies that the behavior of the 'mutants' will not survive in the long-run.

Assume the system is in a certain state s. Then an evolutionary stable strategy is defined as follows: (e.g. Maynard Smith and Price, 1973; Friedman, 1991; Weibull 1995):

Definition 2 *A strategy (or state)* $s \in S$ *is an evolutionary stable strategy (state) if for every other strategy* $y \in S$*:*
a) $g(y, s) < g(s, s)$ *or*
b) $g(y, s) = g(s, s)$ *and* $g(y, y) < g(s, y)$.

Term *a)* of definition 2 shows that any player that chooses an action y different from strategy s and which appears not to be a best reply to the other players' strategy, s is an evolutionary stable strategy. On the other hand, if condition *a)* fails to hold, a strategy can also meet evolutionary stability by condition *b).* In this case the payoff of strategy y different from s should be equal to the payoff of the current strategy s, but the fitness of strategy s should be higher than that of y. To put it differently:

> [..] even if (s,s) is only a weak Nash equilibrium, that strategy pair can still be an evolutionary stable strategy provided that s can defeat any other strategy y when the population consists almost entirely of players of y. In effect, the first condition says that the home team prevails when it can beat any intruders, provided it can beat any such intruder on the latter's own home field (Hirshleifer and Riley, 1992, p.336).

Definition 2 can also be expressed in a different way. Assume that a certain share $\epsilon \in (0, 1)$ of mutants appears in the population and that all players of the mutant group follow the rule to play strategy $y \neq s$. A logical result is then that the share $1 - \epsilon$ play (current) strategy s. Furthermore, let's presume that the game is played repeatedly by two randomly matched individuals. From the above it follows directly that an opponent plays strategy y with probability ϵ and it plays s with probability $1 - \epsilon$. In terms of mixed strategies ψ, the preceding argument can also be described by the function $\psi = \epsilon y + (1 - \epsilon)s$. Given this expression, the two conditions of definition 2 can be replaced by the single inequality

$$g(y, \psi) < g(s, \psi). \tag{2.1}$$

Following definition 2, a strategy s is an evolutionary stable strategy if equation (2.1) holds, implying that a sufficiently small share of mutants $\epsilon > 0$

cannot ‘invade’ the population; the mutant strategy will eventually not survive. Evolutionary selection thus favours the prevailing strategy s if it has higher fitness compared to the fitness of a mutant strategy y.

Evolutionary equilibrium

Although evolutionary stable strategy is a Nash equilibrium refinement, it still is a static concept. To incorporate dynamics, the evolutionary stable strategy concept should be modified. Game theorists therefore developed the ‘evolutionary equilibrium’ concept (e.g. Hirshleifer, 1977; Riley 1979; Hirshleifer, 1982). An evolutionary equilibrium is a *dynamically* stable equilibrium, i.e., a state that will be reached again and again whenever the system (or dynamic process) is subject to small shocks and perturbations. Like evolutionary stable strategy, an evolutionary equilibrium is also determined by the payoff structure. However, in addition to this, an evolutionary equilibrium is also subject to a dynamic process that determines the adjustment path of payoff differentials. It shows the convergence to or divergence from a possible equilibrium and thus reflects the limiting behavior of the system. (e.g. Taylor and Jonker 1978; Zeeman, 1980; Hirshleifer and Martinez Coll, 1988; Friedman, 1991; Hirshleifer and Riley 1992). Formally (Friedman 1998, p.27):

Definition 3 *A state $s \in S$ is an evolutionary equilibrium if every open neighborhood $\mathcal{N} \subset S$ of s has the property that every path sufficiently close to s remains in $\mathcal{N}$ and converges asymptotically to s.*

An evolutionary equilibrium is a state or strategy that can represent both a population fractionally distributed over a set of strategies (heterogeneous mode) or a situation where all members of the population use the same strategy (homogeneous mode). To summarize: an evolutionary equilibrium is a stable terminus, implying that the evolutionary adjustment process restores the distribution whenever the process is affected by sufficiently small arbitrary shocks.

Equilibrium relationships

Now that we have provided an overview of the three main equilibrium concepts, the next question is: how are they related? In one-dimensional models with a bilinear payoff function g and under the assumption of replicator dynamics M_f, the following relationship between the three equilibrium concepts outlined above can be made (e.g. Van Damme, 1987; Friedman, 1991):

$$ESS(g) \subset EE(M_f) \subset NE(g). \tag{2.2}$$

From 2.2 we see that Nash equilibrium is necessary and evolutionary stable strategy is sufficient for evolutionary equilibrium. Normally, one can compute the Nash equilibria directly from the stage game with payoff function g. Then one of Friedman's (1991) conclusions is that the evolutionary equilibria of *any* dynamic F all coincide with Nash equilibria of the payoff function g.

So far, we have discussed the main elements and features of evolutionary games with a biological flavour. It is now time to move towards the economic applications of evolutionary game theory.

2.4 Evolutionary games in economics

Recall that in the biological field evolutionary game theory was defined as a way of thinking about evolution at the phenotypic level with frequency dependent fitness. However, for our purpose we need a definition that is justified in an economic sense, i.e., we have to make the step towards a definition that easily can incorporate economic variables.

Recently some textbooks have appeared, describing the theory of evolutionary games in relation to economics, or more broadly, the social sciences. Weibull (1995) introduces evolutionary game theory by starting the discussion on static and dynamic approaches in relation to non-cooperative game theory. He emphasizes deterministic continuous time dynamics. Vega-Redondo (1996) is another textbook in the field. He mainly focuses on stochastic evolutionary games and also discusses socially oriented applications. Samuelson (1997) describes the usefulness of evolutionary game theory as a tool for equilibrium selection. Young (1998) devotes a book to the emergence of conventions in societies and the transition between conventions. He particularly develops an evolutionary game framework with stochastic components. The book basically draws upon the cutting edge work of Kandori *et al.* (1993) and Young (1993). Hirshleifer and Riley (1992) devote a chapter to Nash equilibrium and its evolutionary refinements. More recently, Gintis (2000) has provided an extensive overview of evolutionary game theory and social sciences in a broad sense.

The studies of Weibull (1995), Vega-Redondo (1996) and Samuelson (1997) remain to a large extent in the sphere of abstract theory. However, Gintis (2000) also aims at discussing real social life examples and dilemmas in which strategic interaction is present. Gintis' problem oriented approach has two main predecessors: namely Friedman (1991, 1998). Although Gintis (2000) connects evolutionary game theory to a broad range of potential topics, the main advantage of Friedman (1991, 1998) is that it provides one coherent unified evolutionary framework, hence making it suitable for any 'n-dimensional' application. In turn, the application of evolutionary games becomes much easier in this way and we therefore adopt Friedman's way of modelling and take his characterization of an evolutionary game as starting point. To confine the field of evolutionary games, we adopt the following definition (Friedman, 1998, p.16):

Definition 4 *An evolutionary game is any formal model of strategic interaction over time in which:*
a) higher payoff strategies tend over time to displace lower payoff strategies;
b) there is some inertia;
c) players do not systematically attempt to influence other players' future actions.

These assumptions do, of course, have some implications when they are 'translated' to economic problems. The implications for our oligopolistic model will be discussed in chapter 6. In this section we solely discuss the definition in a more straightforward manner without considering possible drawbacks of the actual application.

2.4.1 Monotonicity and compatibility

Higher payoff strategies tend over time to displace lower payoff strategies. This monotonicity principle simply means that strategies or actions with a higher payoff crowd out lower payoff strategies. Monotonicity thus implies a dynamic that selects in favour of the better performing strategies and hence makes the higher payoff strategies become more prevalent in the population.

There are many forms of (evolutionary) selection dynamics. Recall that the research identified in the biological science often assumes the replicator dynamic. However, as Friedman (1991) points out, for economic or social applications, the assumption of a genetic mechanism that underlies the replicator dynamic might be too strong and 'in economic applications, genetic transmission may sometimes underlie important constraints but generally has too much inertia to produce interesting dynamics over relevant timescales' (Friedman, 1998, p.17). There are some studies that use replicator dynamics. One is

Hansen and Samuelson (1988). They test the previous mentioned *as-if* hypothesis by considering a game theoretical environment in which economic agents do not optimize explicitly, but use simple decision making rules. Their study validates the previous mentioned evolutionary hypothesis, provided that the single economic actor's effect on the other players' payoff is negligible. This result directly relates to the large population assumption of evolutionary game theory.

With respect to the monotonicity principle, Friedman (1991) introduced the term compatibility, which implies that the payoff function and the selection dynamic are interrelated. So the only requirement for compatibility is monotonicity. Looking more carefully, this single requirement actually implies that, when applied to economic problems, one does not have to know the full details of the corresponding learning or adjustment processes on which the particular problem is based. In this way compatibility is one of the main advantages for applied work. Experimental research is expanding and may result in better insights into what kind of learning (adjustment) dynamic describes specific economic environments best. However, at this stage it is too early for our problem to exactly know which dynamic to apply. Therefore, we adopt Friedman's compatibility condition without specifying a very detailed dynamic in advance.

2.4.2 Inertia

The process of adjustment should be characterized by gradualism. Too abrupt changes in the aggregate behavior of the population are ruled out, paving the path for 'smooth' behavior of the system. The inertia condition reflects evolution. The principle makes a sharp distinction between evolutionary change and revolutionary change as Friedman (1998, 2001) points out. The adjustment process in a biological sense is very slow and might even be too slow as an appropriate approximation for an economic adjustment dynamic. But the essential point is the absence of discontinuities[8].

Not meeting the inertia condition implies so-called 'temporal lumpiness' (Weibull, 1994). Temporal lumpiness means that the evolutionary selection dynamic exhibits volatile stages due to e.g. simultaneous jumps in behavior by a large fraction of the population. According to Weibull (1994), this could only

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[8] More technically, the inertia condition can be met by assuming that the adjustment dynamic is Lipschitz continuous. Lipschitz continuity of a function $f : X \to R^m$, where $X \subset R^m$, holds if for every compact subset $B \subset X$ there exists some real number λ such that $\|f(x) - f(y)\| \leq \lambda \|x - y\|$ for all $x, y \in B$.

be an obstacle in case of discrete time selection dynamics. Temporal lumpiness is then, to a large extent, a rather artificial obstacle. It is, however, not a problem under continuous time dynamics. This is also one of the reasons why we use continuous time dynamics.

2.4.3 Game against nature

The case where players do not systematically try to influence other players' actions and take current and future behavior of the other players as given, is referred to as a Game Against Nature. According to Friedman (1998, 2001), the GAN condition could refer to either price taking behavior, implying a large number of players, or to players acting myopically. The former argument implies a perfectly competitive environment. Since our analysis will emphasize imperfect Cournot competition, it is natural to presume that a player acts in a myopic way by only considering the present observable quantity actions of other players in making his strategy choice. The player does not consider whether and how competitors might react to his actions and consequently she does not try to anticipate on such reactions. How the set of strategies evolves over time, is simply the product of myopic strategy choices. By considering only these types of strategy choices, we explicitly meet the GAN condition.

2.5 An evaluation

Based upon the previous discussion, we will now summarize the main features of evolutionary game theory. We distinguish four main advantages of adopting an evolutionary framework compared to a (neo)classical one. They are related to the following issues: the nature of adjustment, stability testing and selection of equilibria, a nonlinear payoff structure and empirical testing.

Qualitative behavior and adjustment velocity

Evolutionary game theory can provide insight into how a possible equilibrium is reached. Contrary to classic equilibrium models and classic game theoretical models, it explicitly addresses the characterization of the dynamic adjustment path. In this regard there are two dimensions: the direction and speed of adjustment.

First, the direction of change. This is an intuitively straightforward aspect. Evolutionary games show under which states of the system strategy adjustment is negatively or positively sloped. A negatively sloped adjustment path of a particular strategy means that the payoff declines if more players adopt this strategy. The reverse holds for a positively sloped adjustment path: payoffs increase when more players follow the corresponding strategy. In short: evolutionary game theory provides a view into how strategies or states evolve in a qualitative manner by emphasizing the dynamics of the game.

Second, the velocity of strategy adjustment. It is easy to understand that under some circumstances, i.e., states of the system, the evolutionary process is characterized by fast adjustment, whereas other states exhibit a relatively slow adjustment speed. The velocity can directly be retrieved from the qualitative behavior. The larger the absolute value of the slopes, either negative or positive, the faster the adjustment.

Stability testing and selection

In many situations multiple Nash equilibria may exist. By including an evolutionary adjustment process, a dynamic stability criterion is added which can show which Nash equilibrium is more likely to be selected, depending on the initial state and the size of the region of initial conditions whose paths converge to the specific Nash equilibrium (basin of attraction). So, evolutionary game theory can act as an equilibrium selection device.

The selection of equilibria implies testing whether or not equilibria are stable. For example, emergence of evolutionary equilibria is based on dynamic stability criteria. Obviously, the current argument does not hold when there is a unique Nash equilibrium. In this case, standard game theory in a population game would also provide you the right answer and so evolutionary game theory does not have much interesting to add here. In advance of the discussion of research results, we can say that the specified Cournot model also yields only one unique equilibrium. But for sake of completeness the rationale of equilibrium selection and stability testing is included in the current overview.

Nonlinear payoffs and equilibrium structure

There are two options for specifying how the payoff depends on the state s: linear or nonlinear. In case of linearity, adjustment is either positively or negatively sloped under *all* states of the system. So, linear state dependent payoffs always belong to one of these two cases. Under such conditions, classic game theory (in terms of population games), directly provides the correct answer and one actually does not have to consider evolutionary modelling features.

This is not true when payoffs depend in a nonlinear fashion on the state variable. Nonlinearities can introduce different behaviors under different states. At a certain state the payoff might be positively sloped whereas it might be negatively sloped at other states. Then classic game theory is of no use. Evolutionary game theory helps you to distinguish between these two cases, but is especially helpful when there are nonlinearities in the payoff and/or structural changes in the payoffs, so that a bifurcation to a new equilibrium structure emerges.

Equilibrium concept and empirical testing

Recall that an evolutionary equilibrium is a limit point in the evolutionary process and that evolutionary equilibria are a subset of the Nash equilibria. A relevant issue in this respect is what equilibrium concept is most useful in applications. So, how can possible empirical results be made accessible for the theoretical model? Evolutionary equilibria seem a perfect notion to focus on when the theoretical model should be made suitable for empirical testing. That is, evolutionary equilibria serve as basic predictions for observables (Friedman, 1991, p.651). Or as Friedman (1998, p.27) states: 'Behavior is most easily observed when it has settled down, i.e., when the state remains near a fixed point. If the dynamic is not too sluggish or noisy, then most of the time the state should be near an attractor. Some theoretical literature emphasizes limit cycles and even more complex attractors called chaotic or strange attractors but the corresponding behavior will be difficult or impossible to observe in most applications; then, the usable empirical evidence will generally come from states near an evolutionary equilibrium.'

Equilibrium existence

Above we have argued that an evolutionary model could help in selecting equilibria in case of existence of multiple equilibria. At the same time, this advantage also brings a drawback. When out of a set of Nash equilibria some equilibria are selected and characterized as either an evolutionary stable strategy or evolutionary equilibrium, it might be that they do not exist. The justification for using an evolutionary framework then gets somewhat crumbled. If the equilibrium does not exist, why bother using an evolutionary model? One can somehow bypass the obstacle by determining the existence of an equilibrium prior to applying evolutionary techniques. For example, the industrial organization literature has proven the existence of an interior Nash equilibrium for Cournot markets (e.g. Vives, 1999). Then, by applying evolutionary techniques, the chance of nonexistence of the possible evolutionary equilibrium is implicitly reduced.

2.6 Application to the Cournot market and diffusion

This section examines how to obtain an oligopolistic model with all the evolutionary game elements in accordance with definition 4 as given in section 2.4. We do so by especially addressing it in a qualitative way, i.e., the intuitive rationale behind the formal modelling will be emphasized. When everything has been made clear in this sense, we can step forward to the quantitative modelling aspects in chapter 6 more directly.

Recall from definition 4 (section 2.4) that there are three main elements which distinguish evolutionary games from other game classifications, viz. monotonicity, inertia and Game Against Nature. Furthermore, the thesis subject is the diffusion of an advanced pollution abatement technology through the impact it has on the prices and costs of firms who sell their products on an imperfect competitive market. The questions are: which forces drive the diffusion process of the clean technology, whether there is a diffusion equilibrium and whether the clean technology will crowd out the dirty technology. Since the three evolutionary game elements have been examined more generally in section 2.4, the current section elaborates systematically on the elements in relation to a Cournot product market and the technological diffusion issue.

First monotonicity. Strategies that do well have a tendency to grow and replace the strategies that do worse. We now know that monotonicity is narrowly connected to the notion of compatibility, i.e., a way of expressing the relationship between the payoff function and the direction of change in the population fractions regarding the spreading of strategies. So to accomplish such a relationship we need two things: a payoff function and the dynamics governing the switching dynamics between strategies. In economic applications plausible specifications of payoff functions are in terms of e.g. utility, profits or wealth. In our model the difference in profits between firms using the dirty and clean technology could be a suitable payoff criterion. Before we go to analyze such a modelling setup in depth in chapters 6 to 9, we will now first give a brief qualitative flavor of the essential features.

In our case, there is a single population of firms that act in a product market and each firm can choose between two pure strategies: to adopt a standard (dirty) technology or to adopt a pollution abatement (clean) technology. Given the current distribution of technologies across the industry, the choice and implementation of the clean technology yields a certain level of short-run profits, which is either higher or lower than when using the dirty technology. The difference in short-run profits between firms employing the clean technology and firms producing their products with the dirty technology, could serve as an incentive for technology switching. The significance of short-run differentials (or short-run equilibria) as a device for changing behavior and subsequent long-run equilibrium effects, was already noted around the 1870s by Leon Walras. More recent applications in which strategy switching is based on short-run profit differentials, and which are also of interest for the current dissertation subject, are e.g. Sonnenschein (1982) and Friedman and Fung (1996). Furthermore, the short-run profit differential as the theoretical basis for the dynamics of diffusion is a logical one since both theory and empirics show that accruing profits is one of the main drivers for technology adoption (*cf.* Adeoti, 2001).

When talking about the distribution of technological regimes across the population of firms, one encounters the element of frequency-dependency. As firms switch from one technology to another, and, for example, more and more firms adopt the clean technology, this instantaneously adjusts the short-run profit levels of the technological modes. This is the frequency dependent relationship in this case. So, the process of adjustment, i.e., technology choice based on the short-run profit differential of the two modes, depends on the fractions of the population that employ each of the two technological modes. The process comes to a halt when the short-run profit differential is zero; the profits for every technology mode are equal given the state of the system, i.e., distribution of technologies across the industry. Then, the incentive is gone to switch among technologies and the system is in a steady state. So, monotonicity and compatibility are introduced in our model by making the direction of technology change contingent on the profit differential, specifying it as a monotonic functional relationship.

Second, inertia. The adjustment process, representing the degree of technology diffusion, resembles dynamics at a population wide level. It should intuitively be clear that technology diffusion is a natural way for attaching to the inertia element, i.e., pivotal in the diffusion of technology is time and the common features of diffusion are sluggishness and gradualism (e.g. Karshenas and Stoneman, 1995). To avoid confusion, the suggested framework exhibits a gradual change at the industry level of diffusion in terms of firms adopting one technological mode and thus detach the other and vice versa. The entry/exit mechanism acts *within* the population. One could also imagine an additional entry/exit mechanism that in the first stage operates outside the industry. This means that the population of firms in the industry is not fixed as in our case, but that potential entrants can increase the population size, hence making the industry size endogenous. However, we do not explore such an extension for two reasons. First, there is an empirical justification. Bresnahan and Reiss (1991) empirically show that the competitive effects of entering firms are negligible in concentrated markets. Since our market of imperfect competition is a concentrated one, we therefore do not incorporate an entry/exit mechanism. However, allowing entry/exit may be a nice extension from a theoretical point of view. Second, due to the nonlinear structure between the payoffs (profits) and diffusion, it is impossible to derive the long-run equilibrium degree of diffusion (and hence the equilibrium number of firms) analytically.

The final element is the GAN condition stating that player's do not try to alter the opponents' future behavior systematically. According to Friedman (1998), the condition could refer to either price taking or myopic behavior of the economic actors. In our case the former argument is not justified since we explicitly deal with imperfectly competitive markets and, by definition, the firms that play on such markets do not act as price takers. Subsequently, in order to maintain a complete evolutionary game structure, the model can only meet the GAN requirement by assuming that the players behave myopically in their technology adoption decision.

Behaving myopically implies focusing on the short-run. Above we argued that short-run profits are an adequate basis for the technology switching game. In this regard the GAN requirement is easily met. In making the decision whether or not to adopt a technology, the firm does not consider how his (non)adoption decision might affect the adoption decision of competing firms. How the set of strategies over time will evolve over time is simply the product of myopic strategy choices of the firms. Besides this, an additional possibility exists for meeting the GAN condition in Cournot markets. Fudenberg and Levine (1998) show that in a Cournot market the attempt or incentive to influence the future play of the other market participants is fairly small and can be considered as negligible. Main reason for this is that the '[..] model implicitly relies on a combination of lock-in or inertia and impatience to explain why players do not try to influence the future play of their opponent' (Fudenberg and Levine, 1998, p.8).

This concludes the brief outline of the formal linkage between the applied economic model and evolutionary game theory. Before proceeding with technological diffusion models, completion of the current chapter occurs by making some concluding remarks.

2.7 Concluding remarks

Although evolutionary views have inspired a number of economists from the early beginnings of economics as a discipline, the formal framework of evolutionary game theory has been developed by biologists from the early 1970s on. Economists recognized fairly soon that their methodology could be fruitfully applied to economic questions, thus providing a dynamic supplement to static neoclassical analysis.

The basic concepts from evolutionary games in biology have their counterparts in economics. A population can consist of competing firms playing different strategies that can yield a higher or lower payoff, depending on the fitness of the strategies and the shares of firms playing the distinct strategies. The basic evolutionary idea is then that strategies with high profits crowd out strategies which yield lower profits, either through elimination of firms or imitation of successful strategies. Such an adjustment process (selection dynamic) might lead to an evolutionary equilibrium, which coincides with the (static) Nash equilibrium.

A striking parallel between the biological and economic versions of game theory is that (static) optimal outcomes result from a selection mechanism, making the fittest category survive[9]. In contrast, the economic games are played on a much shorter timescale than the biological evolutionary games.

The major contribution of evolutionary game theory to economics lies in the first place in a superior, more general modelling of adjustment processes and in the discussion of the stability of the attained equilibria. The equilibria predicted by the evolutionary model are suitable for empirical testing since it is most likely that the empirical evidence comes from states near evolutionary equilibria.

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[9] Though this doesn't necessarily imply that in the long-run no room for the less fitter strategy could exist. This issue will be discussed in chapter 5.