TECHNOLOGY ADOPTION WITH PRODUCTION EXTERNALITIES

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To Gabriella and Giulia

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Preface

The main goal of this thesis is to investigate the reasons why firms do often adopt inefficient technologies even when superior ones are widely available, and to assess their consequences. From a macroeconomic perspective it has been emphasized that differences in the adoption and diffusion rates of technology have a significant impact on economic growth and development, affecting output and productivity differentials among countries. The importance of these issues explains why the understanding of the determinants of technical change has attracted a great deal of attention by both theorists and applied economists.

A firm's technology choice and its timing rests on the expected costs and benefits of adoption, which in turn are a function of a number of microeconomic and macroeconomic factors. Several such factors have been investigated in the literature, giving rise to patterns of technology adoption more or less successful when brought to the data. One single feature of technology adoption that is widely emphasized is the role of technology-induced spillovers. This dissertation, after surveying the major approaches to technology adoption found in the literature and stressing their drawbacks, studies the effects on firms' choices of technology-induced production externalities that are largely consistent with the empirical evidence and whose relevance has not been previously assessed. The thesis central claim is the existence of a causal link between the effects of firms' choices of a technology and wages. The choice of technology determines an increase in workers' productivity and consequently an improvement of their occupational alternatives, that can transfer on the wages a firm must pay in order to retain its employees.

It is shown, first in an efficiency wage partial equilibrium framework and then in a simple general equilibrium setting, that the presence of production externalities of the sort described above can lead to inefficient technology adoption by firms, so that they may not have an incentive to upgrade to the technological frontier, remaining stuck with old and inefficient technologies. Finally, the possibility of technology misallocation is investigated from a normative point of view, characterizing Pareto-efficient allocations and discussing the role of government interventions to overcome or mitigate market failures.

During all stages of research and writing of this thesis, I have enormously benefited from the constant support, encouragement and guidance of my supervisors, Prof. Volker Böhm and Prof. Gerd Weinrich, who I wish to thank for countless stimulating discussions and for all their criticisms. Over the years, I have discussed various parts of this dissertation with a number of friends and colleagues. Although it would be too long to thank all of them individually, and at the risk of forgetting somebody, I am particularly indebted to Prof. Andrea Boitani and Prof. Umberto Galmarini for their valuable comments and criticisms on previous versions of the core chapters of the thesis. I started developing the ideas in this dissertation while pursuing my Master degree at the University of Pennsylvania; I wish to thank Prof. Boyan Jovanovic and Prof. Andrew Postlewaite for their encouragement and guidance in the early stages of this project.

Parts of the dissertations have been presented at seminars, workshops and conferences in Bielefeld, Copenhagen, Genova, Jena, Milano, Paris, Trieste, Urbino, Venezia and Wien, whose participants I thank for their feedbacks. Finally, I thank my wife Gabriella, not only for all her useful remarks and comments, but for her incredible patience, constant encouragement and support, without which this thesis would not have been completed. I am of course entirely responsible for all remaining errors.

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Introduction

There is a wide agreement among economists and policy makers that technology is a major engine of development and growth. The forces governing innovation as well as the adoption and diffusion of technologies have attracted the attention of both theorists and applied economists, and it is generally agreed that one of the fundamental determinants of economic growth and of changes in productivity is the adoption and diffusion — even more than the invention — of new technologies. The processes leading to the adoption of a technology, however, are far from simple and well understood, and their investigation poses a number of puzzling issues.

As Rosenberg (1976a, p.191) put it, there are two striking "characteristics of the diffusion process: its apparent overall slowness on the one hand, and the wide variations in the rates of acceptance of different inventions, on the other". Although superior technologies are available, many countries remain often stuck with old techniques, which certainly contribute to explain the significant and persistent differences in output levels that are observed, and the tendency to a widening gap in technology adoption between the US and the major Western European countries and between the latter and the great majority of less developed countries (see, for example, Maddison, 1995, Ben-David, 1994, and Sala-I-Martin, 1994). As noted by Lucas (1990), the fact that more capital does not flow from rich countries to poor countries is at odds with economic theory, and more so in a world characterized by high (physical and human) capital mobility and by rapid diffusion of information. Quite similar considerations hold when one takes a microeconomic view point. It is often the case that superior technologies are available and well known within a given industry, but firms are not as quick as expected in jumping to the technological frontier, even when such a jump is not that costly.

The investigation of the reasons why not all countries and firms adopt the best available technologies, or of why not all of them use technology as a driver to promote economic progress and profits to the same extent, has stimulated an impressive body of research and prompted a variety of explanations on the engines of technical change and its apparent slowness. What technologies are adopted and used is the solution to a twofold problem. First, they are obviously the more or less intended result of invention. Second, regardless of their theoretical impact, only those techniques that get to be adopted, and diffuse, play effectively a role. In this dissertation we focus on this second problem and, narrowing further down the object of our investigation, we concentrate on the determinants of the choice of a technology by a firm.

Although it bears many important macroeconomic implications, the decision to adopt a technology is ultimately an individual one, made by comparing the marginal benefits of adoption — often to be evaluated under uncertainty and in presence of limited and asymmetric information — with the costs of scrapping the technology currently used.[1] Hence, the

[1] In this perspective, the diffusion of a technology is, at the end, the aggregate outcome of the individual decisions to adopt it. It is, however, to be noticed that individual decisions are affected in several respects by others' decisions (that influence, for example, the number of users, the definition

choice and the timing of adoption are a function of its expected benefits and costs, that are eventually affected by the economic conditions of the country (industry) in which the firm operates. The core of the problem lies in identifying the determinants of such benefits and costs.

To do so requires, in turn, to be more precise about what technology is. Throughout the dissertation we construe the concept of technology broadly, interpreting it not only as human and physical capital available to firms (embodied in techniques or machines), as it is often done in the literature, but also as improvements in the organization of production and of labor markets, in managerial and governance practices, or in products' quality (reflecting, for instance, changes in consumers' tastes). More generally, our view is consistent with that of *technology as knowledge* stressed, for instance, by the theories of endogenous technical change that have been developed beginning in the early Nineties (see Aghion and Howitt, 1998, and Grossman and Helpman, 1991, for overviews). The emphasis on knowledge highlights that technology is — at least to some extent — non rival (so that the marginal costs for additional firms to use it are negligible), and that the returns to investments in technology are not fully appropriable. This lack of appropriability entails that the benefits stemming from the adoption of a technology are partly public, in that they do not entirely accrue to the adopter but to other agents as well (firms and individuals alike), by adding to their technical knowledge. Much of the literature on technology adoption has indeed emphasized, both at the theoretical and at the empirical levels, the role played by knowledge spillovers (and by many other sources of technology-induced spillovers), pointing out that in most cases they lie at the heart of the choice to adopt (or to delay the adoption of) a technology.

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of a standard, or the speed at which the benefits and costs of a new technology are assessed), so that the study of diffusion processes is not just a problem of simple aggregation.

It is here worth to underline two further and apparently unrelated issues, to which we will return in the dissertation. First, it has been stressed, both by theorists and applied economists, that the emergence of externalities (spillovers) following the choice of a superior technology renders strategic interactions among the parties affected by the decision about technology particularly important, and likely to influence the firm's choice itself. Second, it is widely agreed that there exists a strong complementarity between recent (after the Second World War) technological advances and workers' skills, that has in turn determined the emergence of a marked skill premium. A recent literature has further exploited this complementarity to link the technology-induced skill premium to the observed increase in wage inequality, both between and within classes, thus suggesting a direct relationship between technology and wages "intermediated" by the process of workers upskilling.

This thesis aims to contribute to the technology adoption literature by building on the two issues reported above, and by focusing on the nexus between the labor market — or better the wage structure — and firms' technological choices. The existence of a relationship between labor (and wages) and technology is certainly not new: the role of labor endowments and the impact of wages on technology adoption and diffusion have been extensively investigated, and some attention has also been devoted to the effects on adoption of the strategic interactions between workers and entrepreneurs.

The novelty of our approach, however, is that it establishes, and assesses the relevance of, a causal link between a firm's decision to adopt a technology and the level of the wages it has to pay afterwards. The basic idea is rather intuitive. When a firm adopts a new technology, its workers may benefit from an upskilling process providing them with the abilities needed to operate the new technology. As far as the advancement in workers' skills is transferrable (for example, when it takes the form of general human capital), increasing productivity in alternative employments, it is likely to induce an improvement of their outside options. This, in turn, results in an increase of workers' bargaining power in their relationship with the firm. Insofar as this translates into higher wages, technology-induced externalities — whose importance is ultimately determined by the weight of knowledge spillovers — affects the firm's incentives to adopt the technology in the first place, possibly delaying or blocking technology adoption.

It is worth reaffirming that our argument is well rooted into the empirical evidence on recent technical change and on the distribution of wages, that — as already pointed out — depicts a marked complementarity between technology and skills, and a surge in wage inequality consistent with (if not caused by) the observed patterns of technical change. Both the upskilling associated to the adoption of superior technologies and the resulting increase in wages it induces, together with strategic interactions between workers and firms, are indeed the major building blocks of our theory, adding a further dimension to the debate on technology adoption that has not been emphasized in the literature. Strangely enough, in fact, the impact of technology externalities on the wage structure as a factor affecting technology choices has not received much attention, in spite of the available evidence.

The dissertation is organized as follows.

Chapter 2 presents the major stylized facts that theories of technology adoption and diffusion have to face, and discusses the main theoretical contributions to the investigation of technological choice advanced in the literature, broadly organized according to the determinants they focus on. A special attention is devoted to the engines of technological change (the role of complementarities, of strategic interaction and of labor markets and wages) that are closer to the spirit of those emphasized in the dissertation, so to render evident the similarities and differences in their treatment by alternative approaches.

Chapter 3 introduces the conceptual framework that constitutes the guiding thread for the models formulated in the core chapters of the thesis. The chapter's goal is twofold. First, it discusses the building blocks of the adopted setting confronting them with the existing literature. In particular, it investigates the link between the externality driven approach of the dissertation and the contributions on strategic complementarities, emphasizing the role of technology-induced externalities and of imperfect competition in the labor market as sources of strategic interaction between firms and workers. Furthermore, as the main theme of the thesis rests on the externalities linking the choice of technology to the wage structure, the chapter assesses their relevance by focusing on the relationships between technical change and wage distribution and inequality.

Second, it develops the formal setting for the models investigated in the core chapters of the dissertation (Chapters 4 - 6), by working out a static reformulation of Shapiro and Stiglitz (1984) efficiency wage setup and illustrating its properties and implications. In particular, it is argued that the adoption of an efficiency wage framework provides a natural way to formalize the wage setting process and to relate firms' technology choices and workers' outside options.

Chapter 4 studies a partial equilibrium model with efficiency wages built for a small imperfectly competitive economy in which consumers can earn a living — and all production activities are carried out — either in the subsistence (self-employment) or in the industrial sector of the economy. The latter is characterized by the presence of one firm only that is price taker in the goods market and a monopsonist in the labor market, and produces a consumption good by using labor as the only input in production besides technology. The key feature of the model is that it assumes the existence of a direct link between the reservation utility of workers and the firm's technology — via technology driven externalities — that renders workers' reservation wages a function of the technology adopted by the firm (i.e. workers' participation constraints endogenous in the firm's technology). The main purpose of the chapter is to investigate the firm's technology adoption problem and to show that the nexus between the choice of technology and wages can be responsible for an inefficient technology to be adopted. A final section illustrates the main ideas and results of the model for a Cobb-Douglas economy, performing a series of comparative statics exercises. The same example will be used to illustrate the framework and results of Chapters 5 and 6.

Chapter 5 further investigates the effects of the links between market power and technology on firms' choices by extending the analysis to a general equilibrium economy, that allows us to fully account for the feedback effects originated by the strategic interaction between the firm and its workers. Although the structural characteristics of the economy are essentially the same introduced in Chapter 4, the link between workers' outside options and the firm's decisions is here modeled explicitly. It is shown that the firm's choice of technology affects workers' productivity when self-employed through a (technology-induced) positive production externality that, in turn, increases their outside options and possibly their wages, thus imposing a negative pecuniary externality on the firm. Technology adoption by the market sector firm is investigated under two different scenarios: one in which the firm takes the externality it generates upon the self-employed workers as an exogenous parameter (that is labeled Cournot-Nash case), and the other in which it takes it into account when choosing technology (the von Stackelberg case). It is shown that the Cournot case amounts to neglect the role of externalities, which implies that the firm's decisions do not entail neither labor nor technology misallocation. Conversely, the von Stackelberg case is one in which the firm is more sophisticated and the effects of externalities are internalized, so that the adoption of a superior technology can be dampened by its expected impact on wages.

Finally, Chapter 6 deals from a normative perspective with the sources of non-marketed relations (pecuniary and production externalities) responsible for the possibility of technology misallocation. First, it characterizes the Pareto efficient allocations that would be achieved by a social planner internalizing all sources of externalities and compares them with the market allocations derived in Chapter 5. Second, it studies alternative government policies to mitigate or overcome market failure. In particular, it is proven that first best subsidization is always capable to achieve Pareto-efficient allocations. Similarly, second best instruments in the form of Pigouvian subsidies on technology are always welfare enhancing, while interventions on labor demand have an ambiguous effect, so that either a tax or a subsidy can stimulate the choice of a superior technology and increase welfare.

A short final chapter contains a brief summary and discussion.

2

The Adoption and Diffusion of Technology: Theories and Empirical Evidence

In analyzing technology adoption and its implications for growth, a great part of the literature has conceptually concentrated on two different issues, either separately or combining them: the problem of technology choice and that of technology diffusion. Furthermore, for the latter, most of the attention has been devoted to the diffusion of new technologies and less emphasis has been placed on the increase of the usage of existing technologies, that however — on the light of the available empirical evidence — is at least as important as the other.

The emphasis on the modelling of the nature and characteristics of the diffusion processes of a technology hides indeed a more fundamental underlying question, related to the identification of the engines of technology adoption. Several explanations on the mechanics of how and why a technology spreads have been advanced, but in many cases they remain agnostic on why a technology is chosen in the first place. Quite obviously, the two issues — of choice and diffusion — are interdependent and, moving backward, understanding the mechanics of diffusion helps ex ante in identifying the best candidates for successful adoption. The investigation of the determinants behind the adoption of a technology, whatever a new or an already existing one, assumes however a prominent role. Such a question can be addressed from many different angles and at many different levels — focusing on the individual adopter's characteristics, or on the properties of the industry in which it operates and, even more generally, on those of the economy at large.

There is a rich empirical literature emphasizing the factors that are most likely to influence technology adoption — and hence productivity growth — and their disparities across countries. A correspondingly rich theoretical literature has developed focusing on these determinants and on the mechanism by which they end up affecting technology choice.

This chapter, starting in Section 2.1 from an analysis of the characteristics and of the more consolidated approaches in modeling technology diffusion, focuses on the factors behind the choice to adopt a technology. Coherently with most of the literature on this topic, and with the framework adopted in the core chapters of the dissertation, the attention is concentrated almost exclusively on real factors (and especially on labor market imperfections), neglecting the role of financial variables or capital market imperfections, without however implying that they do not matter. The discussion of the available empirical evidence (mainly at the cross-country level) in Section 2.2 presents the major stylized facts that theories of technology adoption have to face. Finally, the main section of the chapter (Section 2.3) discusses and evaluates, in the light of such stylized facts, the main theories of technology adoption advanced in the literature, broadly organized according to the engines of adoption they focus on. Section 2.4 contains some concluding thoughts.

2.1 Modeling Technology Diffusion

Almost all empirical studies about technology adoption, beginning with the seminal studies by Griliches (1957) and Mansfield (1961, 1963), stress that the typical technology diffusion curve is roughly S-shaped: adoption is slow at first, it accelerates while spreading among potential users and then it slows down again when the market for the technology becomes saturated. This dominant stylized fact concerning the dispersion in the timing of technology adoption has traditionally been investigated by means of two classes of models.[1] The first, known as *learning* or *epidemic model*, assumes that not all agents (possibly with identical tastes) are informed about the existence of a superior technology at the same time. They are supposed to "learn" about the technology and acquire the knowledge to operate it from their neighbors. Thus, as time passes more people will adopt the technology until the market becomes saturated and the process slows down again. Even though, as observed by Geroski (2000), technologies (especially the new ones) take often longer to be adopted than it takes for information to spread, the epidemic model has the merit to emphasize the role of information flows — typically in the form of technology-induced knowledge spillovers — in adoption and diffusion processes. As we will discuss in some details throughout the chapter, a large and ever growing literature deals with the importance and the impact of spillover effects, emphasizing the variety of forms that the speed, the pattern and the extent of knowledge flows can take.

At the core of the issue stays, however, the widely accepted stylized fact that the knowledge of a technology (and the skills necessary to implement it) is very costly to produce but very easy to reproduce, and that firms are in most cases unable to appropriate all the benefits deriving from the technological innovations they introduce.[2] Both Mankiw (1995) and Parente and Prescott (2000), for example, think at techno-

[1] See Hall (2004), Hall and Khan (2003), and Geroski (2000) for extensive surveys of the literature on technology diffusion.

[2] Bernstein (1988), Nadiri (1993), Griliches (1992), and Geroski (1995a,b), among many others, document the (inter- and intra-industry) spillover effects associated to R&D and technological choices. And Keller (2002a) analyses the spatial distribution of technological knowledge. A further

logical knowledge as a form of knowledge widely available to firms and individuals in all countries, although their views differ on its impact in the explanation of cross-country productivity and technology differences.

The role of information flows and learning in technology diffusion has been the object of careful investigation beside the classical formulation of the epidemic model. A recent stream of literature — that looks at technology adoption as a problem of investment under uncertainty in the *real options* framework developed by Dixit and Pindyck (1994) — argues that information plays a major role in the adopter's decision problem (see, for example, Stoneman, 2001). While the benefits of adoption are mainly received throughout the life of the acquired technology, and are thus uncertain, the corresponding costs are incurred at the time of adoption and are typically sunk (especially those associated to the learning of the technology). The presence of sunk costs of adoption — determining irreversibility of the investment — implies that there is an option value in waiting before sinking the adoption costs, so that firms may have an incentive to delay adoption. It is as if the potential adopter holds a call option to adopt the new technology that can be exercised at any time. As for any other option, there is an advantage to exercise the option when it is "deep in the money" (i.e. when the expected benefits are well above the costs) providing a reason for delaying adoption. When acquiring information on a technology is costly, agents may decide not to acquire "complete" information about its benefits and costs, in order not to incur these search costs. Similarly, the expected benefits of adopting a technology may be difficult to assess precisely at first, increasing the associated risks. Only when time passes and more information is acquired expected benefits and risks can be re-evaluated. The existence of such

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stream of literature investigates the flows of knowledge spillovers based on patent citations data; see, for instance, Jaffee, Trajtenberg and Henderson (1993) and Jaffee, Trajtenberg and Fogarty (2000).

learning and search costs in an uncertain environment, combined with risk aversion, are likely to slow down technology adoption.[3]

This literature is to some extent related to a series of contributions — dealing more generally with the existence of strategic complementarities in discrete choices — on the determinants of implementation decisions and on the possible sources of delays. Shleifer (1986) emphasizes that firms may have an incentive to bunch their inventions and time the adoption of new techniques when aggregate demand and profits are high, exploiting the demand complementarities stemming from the underlying interactions between agents.[4] As for the possible reasons to delay choices, Chamley and Gale (1994) and Gale (1996a) point to the importance of information flows, stressing that agents may endogenously have an incentive to delay their actions, even in the presence of a cost of delay, in order to learn from the information created by others. Similarly, Gale (1996b) emphasizes the fact that the actions undertaken by an agent can directly affect the returns of others, making in some cases rational for the agent to postpone her decisions.

By emphasizing the role of information (and the associated costs of learning), along with that of uncertainty and of the adopter's attitude toward risk, this stream of literature extends the logic of the epidemic model by adding to the picture the consideration of some of the adopter's characteristics — like the costs of acquiring information reflecting her ability to learn and her attitude toward the risk — that remain however exogenously given.

[3] Since uncertainty usually reduces over time, risk taking adopters are the first to choose a superior technology, with risk averse users following (which is compatible with the S-shaped curve).

[4] The model has been one of the first to establish a systematic relationship between growth and cycles via endogenous technology implementation cycles. See also Cooper and Haltiwanger (1993) for a study of the link between the business cycle and the replacement of old machines.

A further stream of contributions (see Arthur, 1989, and Geroski, 2000) focuses on the observation that different variants of a technology can reach the market, and that the first stages of the adoption process require the choice among them. For the first adopters the choice is indeed an investment choice. If, due to several possible factors, one variant is preferred to the others by the early adopters, more information will be generated about that variant. As information spreads, subsequent adopters will be less and less willing to experiment with other variants and herd behavior will be observed (see Banerjee, 1992; and Bikhchandani, Hirschleifer and Welch, 1992), locking adopters in the initially chosen variant. This, in turn, generates bandwagon effects (typically labeled as *information cascades* in this literature), with late adopters imitating the early ones and choosing the same variant, without incurring their costs. The early stage of technology diffusion, being affected by a variety of reasons, may look as stochastic. Only when the choice of a given variant is established and lock-in occurs (a sort of legitimation process) the real diffusion of the technology will start. Quite intuitively, many firms will wait for others to make the initial (costly) choice (i.e. free-riding on their efforts), and only when it becomes clear which variant is the successful one a burst of adoption will be observed; with the whole process likely to give rise to a S-shaped curve. Jovanovic and Lach (1989) and Jovanovic and MacDonald (1994) focus on processes of this type, by emphasizing the role of social learning.

What matters most for the adoption and diffusion of a technology, according to the approach just outlined, are thus the early choices on different variants of a technology, which are the major determinants of the subsequent adoption. The most important open issues consist then in investigating what are the factors determining — or at least influencing — such choices or, in other words, what are the main characteristics of the early adopters and of the "environment" (i.e. industries and countries) in which they operate. The emphasis on the characteristics of the adopter and of the environment are indeed the imprint of the second class of models traditionally used to explain the S-shaped diffusion curve. These models, often labeled as *probit models*, are in fact based on the *heterogeneity* between adopters. In their classical basic formulation (well antecedent the real options approach), these models derive the S-shaped curve by assuming that potential adopters believe that the distribution of values for the new product is normal, that the cost of the product is constant (or monotonically decreasing over time), and that they adopt the new technology when their personal valuation of it is above its cost (or a certain threshold function of the cost). The differences in the timing of adoption are thus related to the heterogeneity of the potential adopters, allowing for the investigation of the impact of several firm- (and country-) specific potential determinants of technology choice.

Although both the epidemic and learning type diffusion models — being able to shed light on the mechanisms by which a technology gets adopted and spread in the economy, and to fit the stylized facts — have been very popular in the technology adoption literature, the fundamental underlying problem of what are the factors driving the choice of a technology deserves further investigation. The following sections focus on this issue, first by summarizing the empirical evidence on technological choice and diffusion, and second by surveying the main classes of theoretical models studying the determinants of technology adoption.

2.2 Empirical evidence and stylized facts

A wealth of information on the determinants of technology adoption comes from cross-country studies investigating the disparities between different economies, both at the macroeconomic and at the microeconomic level (in terms for example of institutions, degree of development, factor endowments, and education). Recent empirical studies show that a significant part of the productivity differentials among countries is due to differences in the used technologies and especially to the delays in the adoption of superior technologies, as emphasized among many others by Caselli and Coleman (2003) and Klenow and Rodriguez-Clare (1997).

Most of the theories studying the cross-country technology adoption problem explain the choice of different technologies in different countries by stressing the role of some sort of transfer and/or adjustment costs.[5] The major problem is then to identify the sources of such costs, or even more fundamentally, the variables affecting technological choices.

A very clear indication emerging from the available cross-country empirical evidence is that the adoption and diffusion patterns of most major technologies have two main common features (see, for instance, Comin and Hobijn, 2004). First, technology adoption follows a trickle down mechanism that is robust across technologies and over time: most technologies are adopted first in leading countries and trickle down, often with substantial delays (although the rate of convergence in technology adoption has increased after the Second World War), to lagging countries that catch-up with the leaders, at least partially.[6] Second, there are significant lock-in effects in technology adoption, meaning that firms continue to invest in non-frontier technologies well after a new technology has been introduced. This second observation restates the stylized fact already stressed above that technology adoption is a slow (S-shaped) process.

A variety of factors influences technology adoption and contributes to explain both the trickle-down adoption mechanism and the firms' lock-

[5] See, among many others, Jovanovic and Lach (1989), Parente and Prescott (1994), Grossman and Helpman (1991), and Anant, Dinopoulos and Segerstrom (1990).

[6] This is widely confirmed by the literature on convergence. See, for instance, Barro and Sala-I-Martin (1997), and Sala-I-Martin (1997).

in in existing technologies. The empirical literature (see, among others, Klenow and Rodrìquez-Clare, 1997 and Easterly and Levine, 2001) has documented a strong correlation between growth rates — and levels — of productivity (technology) and output per capita. This suggests that technology adoption is significantly affected by the level of economic development, and especially so for technologies in the earlier phases of their life cycle, confirming the leading role of rich countries both in the invention and in the diffusion of new technologies. In the long run there are, however, other factors affecting the adoption and diffusion processes of a technology. Econometric investigations (see, among others, Comin and Hobijn, 2004, Caselli and Coleman, 2001, Cohen and Levinthal, 1989, and Wozniak, 1987) suggest that besides real GDP per capita, *coeteris paribus*, education has a prominent role in explaining cross-country disparities in technology adoption. Krueger and Kumar (2004) argue that education, when compared to labor market rigidities or product market regulation, plays a major role in explaining US-Europe technology-driven growth differences. In particular, they maintain that a change in the focus of European policies from skill-specific education towards more general and flexible educational choices at the upper secondary level might reduce the growth gap between US and Europe that has emerged since the mid-1980s. It is interesting to underline that, whereas GDP proves to be important both across technologies and over time, education has played a more important role after the World War II. Moreover, while in the period before 1970 secondary education has been the most relevant educational variable to affect adoption patterns for skill-intensive technologies, in the post-1970 period college level degrees have been the ones to matter most. This is consistent with the view of complementarity among new technologies and college level skills, documented in the literature: see for example Caselli and Coleman (2001), showing that income and human capital are the main determinants of computers adoption (together with trade openness and the overall investment rate in the country), or Acemoglu (2002a) relating the increase in the U.S. college wage premium for the last sixty years to the demand of skilled workers.

Also trade related variables, and especially the degree of openness of a country, play a role in the adoption of superior technologies, not necessarily in the form of direct adoption of more advanced technologies, but seemingly more in terms of knowledge spillovers arising from the relationships with more advanced trading partners, that allow a country to better operate the adopted technologies.[7] Institutional factors play a role as well. Data conform to intuition suggesting, on the one hand, that a more effective executive — in enforcing property rights and in dealing with the potential distortions originated by interest groups — has a positive effect on the intensity of technology adoption. On the other hand, a more "effective" legislative power might have a negative impact on adoption, since it increases the incentives for incumbents to lobby the legislator in order to block the adoption of superior technologies. These incentives are, however, reduced when the degree of party fractionalization in the parliament becomes higher (see, among the others, Grossman and Helpman, 2001). Finally, technology adoption is in many cases positively and significantly affected by the interaction among technologies, and especially by the intensity with which previous (frontier) technologies have been adopted. This suggests that the accumulated knowledge reduces adoption costs, by downsizing the importance of lock-in effects (i.e. reducing switching costs), and — as far as it is transferrable across technologies (meaning that the old and the new technologies require complementary skills at least to a certain extent) — reduces the chances that leapfrogging will emerge.

[7] See Keller (2002b) for a survey, both at the theoretical and empirical levels, on international technology diffusion.

The overall picture that seems to emerge from the cross-country empirical literature is that — besides the role of GDP per capita and human capital (proxied by primary and secondary education, and by tertiary college level education starting in the seventies) — the type of political regime (spreading of parliamentary democracies), and trade openness have been important drivers behind the rapid catch-up of many countries in the post-war period.[8] The degree of homogeneity among advanced countries in terms of the above dimensions has increased after the second world war, rendering technology less localized, as stressed by Keller (2002a). This in turn has implied a reduction of technology adoption barriers, leading towards a more uniform diffusion of technological knowledge across advanced economies (i.e. and thus towards an increase of the speed at which technologies trickle down from leaders to followers). It is, however, important to recall that, although providing useful evidence and highlighting the stylized facts characterizing adoption processes, international comparisons do not reveal the whole set of determinants behind technology adoption, being limited both by data availability and by comparability issues (that necessarily imply to exclude factors that are not available for all countries included in the sample). There are many microeconomic determinants — for which only case or sectorial studies are sometimes available — that are left out of the analysis, even though they are very likely to be important determinants of the choice of a technology, as it will be stressed in the next section.[9]

[8] This literature is closely connected with the contributions dealing with growth and development that emphasize the role of these factors. A recent empirical literature focuses, in fact, on the impact on growth of exogenous factors such as available resources, infrastructures and political regimes. See, for instance, Barro (1991), Sala-I-Martin (1997), Hall and Jones (1997), and Sachs and Warner (1997).

[9] See Hall and Khan (2003) for a recent survey focused on the major microeconomic factors playing a role in the choice of technology, both at the theoretical and at the empirical level.

2.3 Theories of Technology Adoption

Many theories have been developed to explain technology adoption based on different classes of relevant variables. One obvious way to evaluate their "performance" is to make them to face the facts; i.e. to scrutinize their ingredients and logical implications in the light of the stylized facts and empirical evidence. In doing so, the survey in the following pages classifies the different models on the basis of the main engines that are responsible for the choice of technology.

2.3.1 The vintage capital models

One of the most popular theories of technology adoption remains the *vintage capital model*, developed almost half a century ago by Johansen (1959) and Solow (1960) to study the growth of the capital stock both along the intensive and the extensive margin. The main underlying assumption in this type of models is that of a persistent increase in the quality of the new vintages of capital goods. In most models applying the vintage capital model logic to technology adoption (besides the classical references to Johansen, 1959, and Solow, 1960, see, for instance, Laitner and Stolyarov, 2003), the above assumption has the major implication that firms (or countries) have an incentive to invest only in frontier technologies, i.e. those embodying the highest quality capital stock.[10] Once a new vintage has been introduced there is no longer gross investment in older vintages and the fraction of the capital stock embodying older vintages capital depreciates reducing over time. In this sense, new technologies always dominate older ones and, once available, should be implemented instantaneously. At the microeconomic level, this implies that once a superior technology becomes available there should be

[10] Parente (2000) is an exception in that firms do not necessarily adopt the frontier technology when switching technologies.

no firms adopting a different technology, so that firms always adopt the frontier technology only. At the macroeconomic (cross-country) level, vintage capital models suggest that less developed countries, adopting new technologies intensively in order to build up their capital stock, should catch up with respect to richer ones, whose capital stocks remain (at least partly) stuck in older technologies.[11] The fact that countries with lower GDP build up their capital stock by investing in frontier technologies should in turn imply the existence of a negative correlation between technology adoption and real GDP. Unfortunately, however, both implications of the vintage capital model — the adoption of the frontier technology with no delays and the "catch up" hypothesis — are not consistent with the stylized facts described above. Indeed, many technologies are subject to long implementation periods in which older technologies continue to be adopted (meaning that there is a lock-in period in which old non-frontier technologies still dominate) and, moreover, there is no clear evidence of a negative correlation between real GDP per capita and technology adoption. On the contrary, rich countries are typically the first to adopt new technologies.[12] In this sense most of the vintage capital literature, while establishing a link between capital accumulation and technology adoption, fails in explaining the disparities in technology adoption both across firms and across countries.

The question left open by the classical formulation of the vintage capital model on why firms keep adopting non-frontier technologies has prompted, since the early 1990s, a new stream of literature often referred to as *vintage human capital models* (see, for instance, Jovanovic

[11] The same holds true at the firm level. Firms having invested in relatively new vintages of capital stock have an higher opportunity cost (especially if the installed capital is specific and hence the capital costs are sunk) to switch to a superior technology with respect to firms with older and less valuable vintages.

[12] There seems, however, to be a correlation between the economic cycle and the scrapping of old technologies, with increasing rates observed during recessions. See Caballero and Hammour, 1994.

and Nyarko, 1996; Chari and Hopenhayn, 1991; and Brezis, Krugman and Tsiddon, 1993). The unifying feature of these models is the idea that operating a given technology workers accumulate experience, or in other words acquire (technology) specific human capital, whose value would be lost (or substantially reduced) if a new technology is adopted, obviously provided technologies are not complementary to a sufficient extent. This fact reduces the incentives to adopt a superior technology, generating a sort of lock-in effect, and explain why firms and workers stick to older technologies and continue to invest in them even when superior technologies are at hand. Jovanovic and Nyarko (1996), for example, show that the scrappage of experience due to the adoption of a superior technology generates a lock-in effect that can be so significant as to prevent the adoption of frontier technologies.[13]

Although economic history provides several examples of situations in which vintage human capital can be important (i.e. technologies for which there is little doubt that the accumulation of technology specific skills can account for the delays in the adoption of technologies that would replace those skills), there are many technologies that do not seem to require significant technology specific skills and many others that are complementary to previously developed technologies, rendering the accumulated experience easily transferrable.

Moreover, as stressed by Brezis, Krugman and Tsiddon (1993) and like in the classical vintage capital model, the countries (or industries) that have invested the most in a given set of technologies should be those

[13] As shown by Jovanovic and Stolyarov (2000), a similar argument holds for physical capital as well. If old capital has a in-house value that is not recognized by the market, there is an opportunity cost in replacing it. As a consequence, the adjustment of technology (in the form of capital inputs) can be delayed. Furthermore, it may be asynchronous even for strongly complementary inputs. Firms may in fact be able to "reduce the fixed costs of repeated upgrades by upgrading an input by a lot, and then waiting for the quality of the other input to catch up" (Jovanovic and Stolyarov, 2000, p. 15).

that have the most to suffer, in terms of loss of accumulated experience (specific skills), in switching to a new technology. This suggests that, if vintage human capital arguments are the main explanations for the observed adoption lags, there should be leapfrogging in the choice of different technologies, and a negative correlation between technology adoption and real GDP per-capita. Thus, as the vintage (physical) capital model, the vintage human capital model suggests that poorer countries should be the first to adopt a superior technology, implying the validity of the "catch up" hypothesis; an implication, however, that is not confirmed by the empirical evidence. Differently from the vintage (physical) capital model, the human capital one predicts, nevertheless, that there is lock-in in older technologies, allowing for the possibility of long delays in technology adoption.

2.3.2 The innovator-imitator model, general purpose technologies and network effects

The unanswered question why richer countries tend to innovate and adopt technologies first, while laggards are slower to adopt and mostly imitate the technologies introduced by the "leaders" has been recently investigated by a further class of models known as innovator-imitator models. Eeckhout and Jovanovic (2002) argue that the prospect of knowledge spillovers flowing from leader countries (firms) to followers may induce the followers to reduce their efforts in order to free ride. Moreover, since by investing more a follower would see reduced its ability to copy others in the future (under the assumption that the more one knows the less can learn from others), laggards do not have an incentive to invest as fast as they would otherwise. This may explain why some firms (countries) innovate and adopt superior technologies first, while others delay their adoption and do not have an incentive to catch up as long as there are free-riding opportunities. Along the same lines, Barro and Sala-I-Martin

(1997), building on a Romer (1990) type growth model, claim that long run growth is driven by the introduction of new technologies by leading countries, while the other countries find it more convenient to copy the technologies adopted by the leaders, due to the lower costs of imitation with respect to invention and development. As far as imitation costs remain low, followers are fast growing and catch up the leaders. However, as more inventions get copied, imitation costs tend to rise lowering the growth rate of the followers that end up lagging behind the leader persistently.[14] Both models, by stressing the strategic role of imitation and adjustment costs, are successful in explaining equilibria in which the (rich) leader countries are the first to adopt new technologies while the others are lagging behind. They fail, however, in identifying the leaders and the followers, that are exogenously given in both cases. In other words, they are unable to isolate the determinants of adoption disparities, and thus to explain one of the two stylized facts discussed above, i.e. the observed lock-in old technologies.

A theory that fits both stylized facts has been proposed in the late nineties by Helpman and Trajtenberg (1998), that focus on the adoption of exogenously given *General Purpose Technologies*. The central tenet of the theory is a rather intuitive one: the first countries to adopt a technology are those needing the least expenses in complementary innovations (technologies) and having the biggest increase in demand when adopting at an early stage. The delay in adopting a technology depends on the time needed to implement complementary innovations.[15] To better understand how complementary innovations are to be intended, it is use-

[14] The main point in Barro and Sala-I-Martin (1997) is to show the emergence of a pattern of conditional convergence. As they stress, in their model of technology diffusion, the increasing costs of imitation play the same role of diminishing returns to capital in the Neoclassical model.

[15] Richer countries are typically those having the more complementary technologies to a new technology already in place.

ful to stress that general purpose technologies are particularly exposed to network effects, relating the value of a technology to the number of agents using it. These effects can be both direct, meaning that the benefit from adopting a technology is directly proportional to the size of the network, and indirect, when the benefit is increasing in the availability of complementary goods. Both types of network externalities, by influencing the expected benefits from a technology, have a significant impact on its adoption, both via a lock-in effect (the incentives to try a different technology decrease in the diffusion of the established one) and a risk-creating effect (early adopters making the wrong choice can end up being stuck with a technology failing to generate the network externalities it is in principle capable of).[16] As mentioned above, this is especially true for general purpose technologies as stressed, for example, by David (1990) — focusing on the introduction of the electric dynamo — and by Brynjolfsson and Hitt (2000), as well as Bresnahan, Brynjolfsson and Hitt (2002) — investigating the diffusion of information technologies — that highlight, respectively, the role of the physical and managerial reorganization of business as complementary innovations to the adoption of a superior technology.

2.3.3 The role of factor endowments

The specific factors most likely to explain adoption disparities still remain to be identified. One first explanatory candidate in this respect relies on the diversities in factors' endowments between countries and industries — or more precisely on the differences in the stocks of physical (i.e. the state of the capital goods sector) and human capital (i.e. the skill level of workers, or the level of education) — likely to generate relevant switch-

[16] See, for instance, Farrell and Saloner (1986), Cabral (1990), and Choi (1997). The impact of network externalities is documented by the empirical literature as well: see, among others, Saloner and Shepard (1995).

ing costs between an established technology and a new one. As stressed by Rosenberg (1976a), if a technology requires complementary skills and capital goods that are costly or need time to be acquired, then adoption may be delayed. Similarly, Mankiw (1995) relates the differences in technology choices and per-capita income across countries to the availability of complementary factors, and particularly of physical and human capital. The same applies to the supply of engineering capacities: if they are inadequate, the step between the conceptualization of the idea and the effective adoption of the technology may take longer. A similar argument holds also for human capital as highlighted for instance by Lucas (1990 and 1993), who stresses the positive link between the level of education and the adoption of advanced technologies, as well as the role of human capital externalities in favoring investment in already rich countries.

From a theoretical perspective, there are several ways in which factor endowments and factor prices can influence technology adoption. On the one hand, a technology can be complementary to a specific factor of production, so that the (marginal) value of the technology is increasing in the level of that factor. As emphasized by Jovanovic (1998), factor-technology complementarity has an important impact on technology adoption: a country (or firm) lacking that factor will adopt the technology (if it does) after a country that has a rich endowment of it. On the other hand, as stressed by Acemoglu (2002a), when the price of a factor is relatively high, firms have an incentive to adopt technologies that allow them to save on that factor (*factor saving technologies*), suggesting that technology and factors of production can be substitute. This explains, for example, why technology adoption tends to be strongly influenced by the prevailing wage rates in the market: the higher the wage rate, the more profitable the adoption of labor saving technologies.[17] Moreover, the

[17] See, more generally, Acemoglu and Shimer (2000) for a discussion of the link between wages and technology dispersion in a setting with costly search to gather information about jobs.

higher the wage rate the higher the value of time and, thus, the higher the incentives to adopt *time-saving technologies*. Hannan and McDowell (1984a, b), for example, illustrate the relevance of this channel for ATM adoption in the banking industry, documenting a strong positive correlation between the prevailing wage rate and the adoption decision. The link between technology adoption and the prices of factors of production is stressed also by Zeira (1998) — with respect to capital goods — who emphasizes that technological progress requires increasing quantities of capital, whose price has thus an impact on technical change.

A further, and more general, channel relating technology and factor endowments (stressed, for instance, by Basu and Weil, 1998, Acemoglu and Zilibotti, 2001, and Caselli and Coleman, 2003) is based on the idea that the successful implementation of a superior technology requires an *appropriate* set of endowments or, more generally, an adequate level of development.

The available empirical evidence tends to confirm that factor endowments, broadly defined, play a significant role in technology adoption. For example, as predicted by the appropriate technology models, Comin and Hobijn (2004) find that the dispersion in technologies across countries is larger than the dispersion in income per capita levels. Among factor endowments, the endowment of human capital plays an important role. For instance, Benhabib and Spiegel (1994) find that the speed at which a country adopt new (typically skill-biased) technologies is related to its human capital endowment. Similarly, Caselli and Coleman (2001) show that high levels of education are an important explanatory variable for the adoption of computers at the cross-country level, confirming the relevance of capital-skill complementarity. More generally, as it will be discussed in greater details in the next chapter, for a great part of the 20th-century (and most so since the Seventies) technical change has been significantly skill-biased (see, for example, Goldin and Katz, 1998). This bias has been a response to profit opportunities, which are in turn a consequence of the increase in the supply of skilled workers. Coherently with this observation, Acemoglu (1998, 2002a) proposes a theory of *directed technical change* based on the idea that technology adoption is directed toward the more profitable areas. Two main factors are responsible for the profitability of a technology: a price effect and a market size effect. The first recognizes that technologies mainly used in the production of more expensive goods are demanded more, so that improvements in these technologies are more profitable. The second points to the fact that technologies that are used by a greater number of workers are more profitable, because a larger market size allows for greater sales and profits. The market size effect is indeed what accounts for the skill-bias in recent technology adoption according to this theory: the more skilled workers are available, the more profitable the adoption of skill-complementary technologies.

2.3.4 Market structure, firm size and strategic interaction

The above discussion suggests that factors of production play a key role in driving technology adoption (and productivity) differentials. Nonetheless, other variables have an important explanatory power as well. Among them, several "supply" determinants — in addition to the availability of complementary inputs (skills and capital goods) — may play a significant role in explaining the patterns of technology diffusion.[18] Examples of these effects are the *technological expectations* about the improvements in a technology after its introduction, the pace of advancements in the technological frontier, the discovery of new uses of a technology (and therefore the expectations on users and market growth), and the im-

[18] See Sutton (1998) for a comprehensive analysis of the links between market structure and technology, and Cheung and Pascual (2001), among others, for an empirical investigation of the effects of product market structure and technology diffusion on productivity differentials.

provements in old technologies stimulated by the introduction of a new one. For instance, Rosenberg (1976b) claims that a rapid rate of technological change may induce a slow rate of technology adoption (diffusion) because of the fear by potential adopters to saddle themselves with a "soon-to-be-obsolete" technology. Conversely, whenever technological change slows down, technology adoption accelerates because of the expectations by adopters that the technology frontier will not move fast. Hence, expectations about the pace of technological advancements play an important role in technology adoption and diffusion.

More generally, on the one hand, the efficiency gains from a technology are much bigger after its introduction (because the imperfections are gradually eliminated, complementary inputs and processes are developed and new markets and uses for the technology are possibly identified), and thus its diffusion is a function of the induced improvements to it.[19] On the other hand, firms producing an existing technology that is a close substitute for a new one can strategically improve their technology, or engage in competitive practices aimed at slowing (or blocking) the diffusion of the new technology.[20]

The industrial organization literature has emphasized the role of strategic interactions between competing firms as a factor that can substantially affect the timing of adoption (see, for example, the early paper by Kamien and Schwartz, 1972 and, for a textbook treatment, Tirole, 1994). Firms (especially those for which a superior technology complements existing activities) may have an incentive to adopt earlier — anticipating

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[19] These observations describe a legitimation process of the new technology similar in many respect to the standard setting processes. On this point see, for example, Katz and Shapiro (1985), and Farrel and Saloner (1985, 1986).

[20] This can contribute to explain the persistence of old technologies and the self-interested resistance to new technology as documented, among others, by Mokyr (1990, 2002). More generally, the role of suppliers, and the degree of upstream competition, in the adoption and diffusion of a technology has been widely investigated in the technology diffusion literature (see, for instance, Geroski, 2000).

that the market will get crowded and returns will decrease — to be able to establish entry barriers to pre-empt rivals, or to exploit product differentiation (on the last point, see Schmalensee, 1982). On a related note, confirmed by the available empirical evidence, incumbent firms are slow in adopting superior technologies in markets where entry barriers are high. Furthermore, firms whose existing activities would suffer from the introduction of a superior technology have an incentive to delay adoption in order to avoid rent-displacement effects.

Since Schumpeter's and Arrow's contributions on the incentives for innovative activity (Schumpeter, 1942; Arrow, 1962) the influence of market structure and firm size in the diffusion of (new) technologies has been widely investigated (see, among others, Reinganum, 1981a,b, and Quirmbach, 1986). The classical Schumpeterian argument points in the direction of a positive impact of firm size and market structure on technology adoption, holding that big firms and those controlling a large market share are more likely to adopt new technologies since they are better equipped to sustain the costs associated to the initial investment in a superior technology. This is so for a variety of reasons. First, only firms having sufficient market power find adoption profitable, since profits are decreasing in the degree of competition. Second, in presence of asymmetric information and hence imperfect capital markets, bigger firms may have an easier access to the financial resources necessary for the introduction of a new technology, besides being eventually better able to attract the human capital and the physical resources that are needed. Third, big firms have typically more diversification opportunities to spread the risks associated to the introduction of a new technology in the presence of uncertainty, that can otherwise substantially slow down the diffusion of a technology (as discussed in Section 2.1). Fourth, the presence of monopoly power renders imitation more difficult and increases the expected duration of rents (see, among others, Davidson and Segerstrom, 1998). Finally, as far as a new technology is generating economies of scale, larger firms are quicker in adopting it because they can capture the economies of scale more quickly and spread the adoption costs across a larger number of units.[21] Since adopting a technology can require costly investments (in terms, for example, of complementary inputs, workers' training, loss of production time, and network effects), in the presence of an uncertain demand, firms are likely to be uncertain whether and when they will be able to recover such costs. As a consequence, it may be possible that they decide not to adopt (or to postpone adoption), even when it is clear that the adoption would increase productivity or product quality. In these cases, being a large and well established firm in the market, and hence having the possibility to count on customers' commitment and stable relationships, can improve the coordination of decisions and the incentives for adoption.

There are, however, strong arguments pointing in the opposite direction and suggesting a negative impact of market power and firms' size on technology adoption.[22] Some theoretical studies have indeed analyzed issues of innovation and diffusion in perfectly competitive environments (see, as recent examples, Boldrin and Levine, 2002a, 2002b). The classical argument — put forth by Arrow (1962) — builds on the idea that in a competitive environment a new entrant has more to gain than a monopolist from the introduction of an innovation, as the latter would

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[21] The Schumpeterian stream of the endogenous growth literature has largely focused on the role of monopoly rents as a stimulus for innovative activity (see, among the others, Aghion and Howitt, 1992 and Segerstrom, Anant and Dinopoulos, 1990). Also, there is a rich empirical literature reporting a positive correlation between firm size and (the speed of) technology adoption. Hannan and McDowell (1984a, 1984b) have found evidence of the relevance of the above factors for the adoption of ATM by U.S. banks in the Seventies. Similar results have been found in a more recent study by Saloner and Shepard (1995). Rose and Joskow (1990) have documented the same correlation for the electric utility industry.

[22] One of the most well known empirical studies finding evidence of a negative correlation between firm size and technology adoption is the one by Oster (1982) focusing on the steel industry.

replace part of its existing profits (rents) by innovating, while such (extra) profits would be completely new for the entrant. Hence, a (perfectly) competitive environment is more favorable to innovation.

Along the same lines, Aghion, Harris, Howitt and Vickers (2001) suggest that product market competition increases firms' incentives to innovate in order to escape it, and that imitation is beneficial in that it promotes more frequent "neck-and-neck" competition. In addition, an increase in competition, by lowering market prices, can have a positive impact on the diffusion of a new technology.[23] Furthermore, the decision making process in large firms may be slow due to excessive bureaucratization, and the adoption of superior technologies can be discouraged by the impact of lock-in or network effects. Large firms may, in fact, have human capital and physical resources sunk in the old technology, rendering expensive the adoption of a new technology that requires different types of resources, as already noted when discussing the importance of factor endowments for technology adoption. The same holds true for networks when the adoption of a technology implies the re-design of the standard on which the network is based; and for firms having a solid customers base, for fears that the new technology will not be well suited for their customers' needs (see, for example, Christensen, 1997).

2.3.5 Trade, institutions and private interests

Other environmental and institutional variables, besides those directly related to the firm's activity or the industry's structure considered above, are likely to be important in technology adoption. One of such variables, investigated by the recent literature in a cross-country perspective, is

[23] Beside the role of technology improvements, the degree of competition in the sector supplying the new technology has an impact on adoption. This has been the case, for example, in the mobile telecommunications industry, as documented by Gruber and Verboven (2001) and Parker and Röller (1997) for the European Union and the United States, respectively.

trade.[24] A major feature of the last three decades has been the increased globalization in production and the greater volume of trade between the OECD countries and the less developed countries.

From a theoretical perspective, trade has several effects. On the one hand, Grossman and Helpman (1991) stress that countries importing more goods get more exposed to new technologies and are, thus, more likely to adopt them. This effect is known as *push* effect: imports embodying new technologies typically imply a high level of knowledge transfer, that in turn induces spillover effects — via a learning process — that are likely to stimulate the adoption of superior technologies. Caselli and Coleman (2001), for example, document the importance of the push effect for the adoption of computer technology and its diffusion across countries; and Caselli and Wilson (2004) generalize the analysis disaggregating the imports of various types of equipment and explaining the differences in investment composition in terms of the degree of complementarity of each type of capital with other factors whose abundance differs across countries. Moreover, in the second half of the Nineties a number of papers has emphasized the existence of a relationship among productivity levels and investments in research and development by trading partner, confirming the relevance of international R&D spillovers and thus the importance of trade for international technology diffusion (see, among others, Coe and Helpman, 1995; Coe, Helpman and Hoffmaister, 1997; and Keller, 2002b, for a review of the subject).

[24] See Keller (2002b) for a comprehensive survey discussing the significance of further channels of international diffusion of technology in addition to trade, and namely the impact of foreign direct investment. Recent works have shown that international technology diffusion is an important source of productivity growth and of per-capita income differentials in OECD countries (see, among others, Eaton and Kortum, 2001, and Keller, 2002a). Furthermore, as stressed by Keller (2002b), its importance is even more evident in poorer and developing countries, for many of which foreign technologies are likely to be the most important sources of productivity growth . Strong technology diffusion, by equalizing differences in technologies across countries, qualifies thus as an important force toward convergence in income, especially in a world experiencing increasing levels of economic integration.

On the other hand, Holmes and Schmitz (2001) consider a model in which domestic producers use a significant amount of resources in order to protect themselves against foreign competitors.[25] These attempts are, however, unable to effectively protect domestic producers against foreign competition — the argument goes — and, when trade barriers are eliminated, firms start spending their resources more productively to sustain the international competition, which in turn promotes innovation. This is a *pull* effect: trade liberalization forces firms to become more competitive, reducing the monopoly power of domestic firms and stimulating technology adoption as a result (as well as the efficiency in the utilization of domestic resources and in pricing behavior).

Finally, a third and related effect of trade passes through the change in relative prices, affecting technology profitability. As argued by Acemoglu (2003a), trade creates a tendency for the price of skill-intensive goods to increase and this (via the price effect discussed in Section 2.3.3) directs technical change, by rendering skill-biased technologies more profitable and thus stimulating their adoption.

Comin and Hobijn (2004) find that trade exposure and international competitiveness, via the combination of the three effects just described, might have played a non-negligible role as a driving force behind technology adoption for the majority of the world most industrialized countries, especially after the Second World War.

A further set of variables likely to contribute significantly in shaping technology adoption is related to the role of institutions: ranging from the design of the political institutions and of the legal system themselves to the potential influencing power of private (social, political and economic) interests. Economic history (see Comin and Hobijn, 2004, for

[25] This has been often argued to be the case for the manufacturing sectors of developing countries, that have traditionally been protected and heavily regulated. On the point and its implications see Tybout (2000).

anecdotal evidence) provides plenty of cases in which the introduction of a new technology threats the interests of some categories of people that, therefore, try their best to prevent its adoption in order to continue appropriate the rents granted to them by the previous technology. For example, this might be the case of unions representing workers being displaced by the adoption of labor saving technologies. At the opposite, but for the same reasons, there are agents — those controlling a specific technology — pushing forward its adoption in order to reap the rents it yields: for example, firms supplying a specific technology getting involved in lobbying activities to keep or increase their market power.[26]

It is immediate to see that the conflicts among different interests may result in significant barriers to technology adoption. Parente and Prescott (1994, 1999, 2000), for instance, emphasize the importance of this type of factors in blocking the adoption of superior technologies. They focus on the role of monopolistic agreements, showing that the existence of a coalition of labor suppliers, selling their input under monopolistic conditions to all firms, can prevent the entry in the industry of other coalitions (of workers) having access to a superior technology, but over which the original coalition does not have monopoly rights, blocking therefore its adoption. They also show that the elimination of these barriers promotes the adoption of superior technologies and leads to significant increases in productivity, proving to be an important determinant of the level of development.

The self-appearing importance for technology adoption of institutional factors, and of the issues related to the enforcement of property rights, prompted a literature on the impact and (endogenous) design of different

[26] Caballero and Hammour (1998), for instance, argue that technology choices are influenced by the presence of specific quasi-rents — with "appropriated" factors excluding the others — and stress the role of institutions, in the long run, to alleviate the macroeconomic consequences of rent appropriation.

institutional frameworks. Not surprisingly, there is a wide consensus that democracies, along with strong and well developed judiciary systems, are better equipped to preserve property rights and prevent interest groups from blocking the adoption of superior technologies.[27] Institutions play an important role in determining the enforceability of contracts as well, which in turn can have relevant implications on the adoption and diffusion of new technologies. As shown by Cooley, Marimon and Quadrini (2003), as far as entrepreneurs enter into long-term contract relationships with financial intermediaries, limited contract enforceability, by inducing financial frictions, can substantially delay the diffusion of specific technologies, adding to the list of complementary explanations for the delays in technology adoption.[28]

On a related note, a stream of literature has investigated the relationship between vested interests' (distorting) influence and the form of government (see, for instance, Bordignon, Colombo and Galmarini, 2003; and for a comprehensive analysis Grossman and Helpman, 2001), showing how the splitting of competencies between central and local governments may reduce the distortions associated to lobbying activities, while local governments are more vulnerable to them.

2.3.6 Government intervention

Technology adoption can be affected in various ways by government intervention, as stressed among others by Hall and Khan (2003) and Geroski (2000). It is well known that there are several interacting sources of si-

[27] See, for example, the discussion in Comin and Hobijn (2004), and especially Lizzeri and Persico (2003). As for the link between property rights enforcement and economic development see, among others, North (1981 and 1991); and, for a theoretical analysis of the impact of the allocation of property rights on innovative activities, see Aghion and Tirole (1994).

[28] This finding is consistent with the evidence discussed by Greenwood and Jovanovic (1999) for information technologies, as well as for other technological revolutions, as reported by Freeman and Soete (1997).

multaneous market failures associated to the development, the adoption and the diffusion of technology. Issues related to the appropriability of a technology benefits, the deterioration of incentives in the presence of spillovers, the misalignment of profits and social benefits, just to cite a few, render the problems associated to technology adoption (and development) quite similar to those posed by public goods (see, for instance, Spence, 1984).[29] There is, then, a need for public intervention. As far as the above problems relate to innovations, the most immediate form of intervention is through the design of patent protection schemes aimed at allocating intellectual property rights, taking into account trade-offs like the one between static and dynamic efficiency, or that between development and diffusion of innovations. This is the object of a vast stream of literature dealing with innovation.[30] However, as our interest is more in the adoption of already available technologies, we focus instead on two of the most direct forms of public sector intervention directly affecting them: fiscal instruments and regulation.[31]

First and foremost governments can use a wide array of fiscal instruments to promote public policies that stimulate or, conversely, slow down (generating switching costs) the adoption and diffusion of a technology.[32] Various types of subsidies are, indeed, available to improve efficiency and

[29] As an example, the presence of knowledge spillovers entails that firms do not reap all the benefits from their investments because of free-riding effects (imitators, in fact, do not suffer the costs of developing the technology), and this reduces their incentives to adopt new technologies.

[30] See Crespi (2004) for a brief survey of the relationships between patents and innovation and, more generally, for a multi-perspective analysis of the determinants of innovation.

[31] In doing so, we leave aside the investigation of many other potentially important issues, such as the impact of institutional reforms on technology adoption and diffusion. It is enough to think, for example, to the possible consequences of reforms that lead to a greater enforcement of contracts, or that affect the distribution of property rights. Furthermore, also informal institutions that are difficult to change in the short run are influenced by institutional reforms; and, in turn, changes in the environment impact on technology adoption processes.

[32] It is important to note that not only the particular instrument used, but also the timing (especially when the choice between different variants of a technology are considered) and the extent

to promote the building up of physical and human capital in order to help the adoption of superior technologies. Furthermore, it is worth noticing that fiscal instruments, besides improving efficiency and help solving problems of "underprovision", can have a direct role also in shaping the characteristics of the adoption process; for example, by introducing taxes to discourage the adoption of old and inefficient technologies.

Second, public policy affects technology adoption through regulation, both directly by means of various forms of economic regulation (via their impact on market structure and competition); and indirectly through more general forms of regulation (not necessarily of a direct economic content). There are, in fact, forms of regulation — for example, those designed for environmental purposes — that can either prohibit or require the use of certain types of technologies, thus dampening or stimulating the adoption of specific techniques. More generally, regulation influences the variables in which firms compete and, in doing so, may direct the adoption of certain types of technologies (as it is most evident in the presence of standard setting policies). Focusing on economic regulation, consistently with what emphasized when discussing the impact of market structure and firm size, interventions granting large market shares to incumbents, and rendering the entry of new firms more difficult, can reduce the incentives to adopt cost-reducing superior technologies, but at the same time increase the expected benefits of adoption if only a limited number of firms is operating in the market. Similarly, antitrust authorities and a regulatory environment promoting competition (as well as the implementation of strategic trade policies) may either stimulate — by lowering prices, providing the right incentives to existing firms, or establishing favorable conditions for new entrants — or slow down — by

(how selective the policy is) of policy interventions are likely to influence the technology adoption process.

eliminating the possible "Schumpeterian" advantages related to firm size and market concentration — the technology adoption process.

Finally, it is worth noting that, besides the impact of the government as policy maker (via its role of tax setting agency and regulator), public procurement can be an important tool of technology policy on its own. The public sector, in fact, is very often a heavy consumer of technology, and an informed one as well as relatively insensitive to price, so its behavior can somehow lead the diffusion process of a technology.

2.4 Concluding Thoughts

The analysis in the previous sections highlighted several issues that theories of technology adoption must deal with. All the available evidence stresses that technology diffusion processes follow a S-shaped pattern, with adoption being slow at first, indicating the existence of (possibly significant) delays in the diffusion of superior technologies. This finding is further confirmed by cross-country investigations, showing that technology adoption follows a trickle down mechanism that is robust across technologies and over time. Most technologies are adopted first in leading advanced economies, and subsequently, but often in a delayed manner, spread to lagging countries. A variety of theories have been advanced to investigate adoption dynamics, mostly focusing on the role of different determinants for the patterns of technology adoption.

There are at least three aspects of the theories surveyed above that are worth stressing once again in the light of the technology adoption framework we will develop in the following chapters. First, the theories most consistent with both stylized facts — the slowness of adoption and the observation that leading firms (countries) are adopting first — are those relating to the so called general purpose technologies. Their key feature is the claim that the first firms (economies) to adopt a superior technology are those needing the least expenses in complementary innovations (technologies) and observing the biggest increase in demand when adopting at an early stage. The first part of the statement amounts to say that the incentives for the adoption of superior technologies increase the higher the complementarity between the old technology and the new one.

Second, both the empirical and the theoretical literature have stressed the role of labor, and more generally of human capital, in the adoption of superior technologies. For instance, the relationship between workers' characteristics and technology adoption, the impact of wages or the role of labor as a complementary or substitute factor of production affecting the choice of a technology have been widely emphasized.

Third, a number of contributions (see, in particular, Parente and Prescott, 1994, 1999) has focused explicitly on the impact of the strategic interactions between workers and firms in the choice of technology, highlighting the role of market power as a "driver" of technology adoption. More generally, the relevance of strategic behavior and interaction among the parties involved in the adoption and diffusion processes has received attention in the literature, especially by the models focusing on the microeconomic determinants of adoption.

As it will become clear in the following chapters, both the complementarity among technologies and the emphasis on labor markets and human capital, as well as the role of strategic issues (namely the interactions between workers and firms' decisions), will be the main ingredients of the models developed starting in Chapter 4 of the dissertation.

3

Technology-Skill Complementarity and Efficiency Wages: a Conceptual Framework for Technology Adoption

3.1 Introduction

This chapter is conceived to lay out the structure and the underlying conceptual framework of the models of technology adoption that will be developed in the dissertation.

In Chapter 2 we stressed that various sources of spillover effects have an impact on firms' decision to adopt a superior technology. We aim at contributing to this debate by highlighting the role of a general class of spillovers (taking the form of production externalities in our most general setting) stemming from the choice of a firm to adopt a superior technology. In the next chapters we will argue that a firm decision to adopt a superior technology may directly benefit its employees, by increasing their wage rates. Intuitively, this is so because once the firm adopts a new technology its workers can acquire a set of "superior" skills that are needed to operate it (we might think as an example to the skills associated to computer literacy). The nature of the "learning" process by which a worker's upskilling takes place is not dealt with explicitly in the dissertation. It is, however, clear that it can take various forms like, for example, learning by doing, on-the-job use, or formal training in the technology. As far as the advancement in workers' human capital is transferrable to alternative uses (improving their productivity elsewhere), it is likely to induce an improvement of their outside options. This, in turn, results in an increase of workers' bargaining power.[1] Finally, to the extent that a higher bargaining power translates into higher wages, technology-induced production externalities (spillovers) may be enough to reduce the firm's incentives to adopt the technology in the first place, thus delaying or blocking adoption.

There are three main ingredients to the argument just outlined: a specific source of *complementarity* between technologies, the existence of *spillovers* (*externalities*) originating from such complementarity and, finally, the presence of *strategic interaction* between workers and firms (combined with specific market structures) affecting wages and, thus, technology adoption. We consider them in turn.

3.2 Technology adoption and strategic interactions

The literature surveyed in Chapter 2 dealing with the determinants of technology adoption stresses the role of several sources of strategic interactions and complementarities, especially between factors of production (and in particular labor, or human capital) and technology. Complemen-

[1] There is a literature in training — somehow related to our argument (although usually taking the opposite perspective that the benefits of market power in setting wages are appropriated by employers) — that investigates the firms' incentives to train in relation to the workers' ex post opportunities, when training is at least partially transferrable, there are poaching externalities and imperfect competition in the labor market. See, among many others, Stevens (1996), Booth and Zoega (1999), Booth, Francesconi and Zoega (2002), and Gersbach and Schmutzler (2001). More to the point, Acemoglu (1997) investigates the interaction between training and innovation and its impact on wages. Similarly, Acemoglu and Pischke (1998, 1999) develop a theory relating the firm's incentive to provide general free training (providing workers with skills that can spill over to other employers) with the degree of the firm's ex post monopsony power and with the presence of labor market frictions compressing the wage structure, respectively.

tarity and strategic interactions are at the center stage in this dissertation as well. The driver of (inefficient) technology choice in the conceptualization briefly summarized in the introduction to this chapter lies ultimately on the increase in wages induced by the adoption of a superior technology, whose extent can possibly be enough to delay or block the choice of the technology by a firm in the first place. The increase in wages following adoption is determined by the strategic behavior of workers in their relationship with the firm. In fact, if as a consequence of the adoption of a superior technology workers' outside options improve (i.e. there is complementarity between technology and outside options), they will require a higher wage to stay with the firm.[2] As will become more apparent in the next chapters, in our framework the main determinant of inefficient technology choices depends on the nature of the strategic interactions between firms and workers induced by the technology itself.

In some respects, our argument is related to that developed by the literature isolating the sources of complementarity and investigating their implications for the behavior of the economy in the framework of coordination games or, more generally, in that of supermodular games (see Milgrom and Roberts, 1990, and, for a textbook treatment, Cooper, 1999, and Vives, 1990 and 1999). Although we do not work directly in such a framework, our analysis bears many conceptual similarities with it. The key feature of the coordination games setting (as developed, for example, by Cooper and John, 1988) is, in fact, that the actions of players are strategic complements, in the sense that they give rise to positive spillovers. Strategic complementarity is such that higher actions (like increased effort or activity) by one player introduce an incentive for the

[2] This argument is somehow related to an idea recently developed by a stream of the innovation literature trying to endogenize the level of knowledge spillovers. Gersbach and Schmutzler (2003), for example, argue that firms may have an incentive to compete for each other's R&D employees since successful bids for a competitor's employee result in a cost reduction for the firm.

others to take a higher action as well, i.e. the best response function of a player is increasing in the actions of the other.[3] In this setting, the inability of agents' to coordinate their choices — what is often labeled as coordination failure — can determine the emergence of a multiplicity of (Pareto-inferior) equilibria.[4]

For strategic complementarities and coordination failures to arise, however, one needs to abandon the standard general equilibrium Arrow-Debreu framework with complete contingent markets. Quite obviously, in fact, in the Arrow-Debreu framework all choices by agents are coordinated through the market mechanisms, there are no frictions and no agents have the ability to influence prices. Moreover, coordination failure can not emerge in a perfectly competitive environment, where the First Fundamental Welfare Theorem holds. Once disposing of complete contingents markets, there are several possible factors that can be responsible for the emergence of strategic complementarity: from production externalities to the presence of imperfect competition and market power, to search frameworks with trading externalities and thick markets, to the timing (synchronization) of economic activity and the externalities induced by information flows.[5]

Both production externalities and market power are going to play a prominent role in our models, even though in different ways than those

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[3] Obviously, the opposite occurs if there is strategic substitutability.

[4] More precisely, strategic complementarity can give rise to multiple equilibria that, in the presence of positive spillovers, can be Pareto-ordered as shown by the literature on supermodular games.

[5] Although not playing an explicit role in our setting, the issues of timing and delay are central to the problem of technology diffusion, as it has been emphasized in Chapter 2. For a more general treatment of the timing, synchronization and implementation of discrete choices see Cooper (1999).

The literature on complementarities and interactions has highlighted also the role of the externalities arising from the trading process, when the Walrasian auctioneer does not work properly. In this case, complementarities rest usually on thick market effects: the more people searching in the market for trading partners, the lower the costs of search. See, for instance: Diamond (1982), Howitt and McAfee (1988), or Kiyotaki and Wright (1993) for a search theoretic model of money demand.

generally emphasized in the coordination games literature. These contributions, in fact, have focused on several different sources of strategic interaction among agents occurring through the production function (technological complementarities), without however paying much attention to the technology choice of firms as a possible source of externalities. As an example, in Bryant (1983), strategic complementarity arises from the assumption that the productivity of an agent is a function of the effort levels exerted by others, and inefficient equilibria (coordination failures) can emerge due to imperfections in the contracting process, or to market incompleteness. More generally, a vast literature with a macroeconomic flavor has been developed investigating a broad range of issues, but technology adoption typically does not play a role neither as an engine of complementarity, nor as an object of investigation.[6]

Similar observations apply to the contributions where the departure from the Arrow-Debreu framework originates from the introduction of imperfect competition. The presence of market power is a source of complementarity in that it is responsible for the strengthening (with respect to the general equilibrium model) of the interactions among agents. In the coordination games literature these interactions are typically induced by the standard Keynesian income-expenditure relationships, a feature common to many Keynesian models of price rigidities. The key feature of these models are aggregate demand externalities stemming from income effects: the higher the output of other producers in the economy, the

[6] The study of the business cycle in presence of strategic complementarities has often been at the center stage in the coordination games literature. To make a few examples, Benhabib and Farmer (1994) study how the presence of social returns to scale affects the stability properties of the steady state equilibrium. Durlauf (1991) investigates how the existence of dynamic local complementarities between neighboring agents can induce multiple equilibria in the absence of shocks. Cooper and Johri (1997) assume that the productivity of a worker is affected by the level of activity of the others and show how i.i.d. shocks both in technology and taste propagate. Finally, Weil (1989) and Bryant (1987) study the emergence of multiple equilibria in presence of technological spillovers arising from the presence of increasing social returns (but constant returns at the individual level).

higher the aggregate expenditure and, as a consequence, the higher the demand and the output of the individual producer. The importance of interactions among producers (in the same or different industries) induced by demand spillovers, together with that of non-convexities in technology, can lead to multiple Pareto-ranked equilibria and coordination failure.[7] It is worth noticing that Cooper (1994), in a study dealing with the correlation of productivity and output in presence of demand shocks, provides an interesting application of the above arguments to a technology choice problem. He shows that, depending on the strength of the linkages in sales across sectors, there might emerge equilibria in which firms have an incentive to choose low productivity (and thus inferior) techniques, even if more productive technologies are available. The idea is related to those we will develop in the next chapters. However, while in Cooper (1994) the choice of technology is determined by spillovers on the demand side (independent from technology), in our framework it will be the technology itself to generate (technology-induced) spillovers ultimately affecting its choice. In this respect, our setting is somehow closer to that proposed by Puhakka and Wissink (1995) who focus on the role of cost externalities in Cournot competition. If applied to problems of investment in technology, their model is such that an increase in an industry's output stimulate R&D investments. Successful innovations, in addition to reduce the costs of the innovating firms, benefit other firms reducing their costs of pro-

[7] Most of the macroeconomic literature on imperfect competition and demand complementarities has focused on two main classes of models, differing in terms of the sources of market power. The first is that of multisector models, characterized by strategic substitutability between a small number of firms in any given market and strategic complementarity across sectors, which depicts the possible emergence of multiple equilibria, underemployment and multiplier effects (see, for instance, Hart, 1982; Weitzman, 1982; and the discussion in Cooper, 1999). The second is that of monopolistic competition, where market power arises from the degree of substitutability between products. In these models, multiple equilibria can arise because of strategic complementarity in prices. See, for example, Blanchard and Kiyotaki (1987), or Ball and Romer (1990), where the multiplicity of equilibria emerges from the decisions of firms to change their prices in the presence of menu costs.

duction because, for example, the knowledge of the technology spills over to them. The two authors, however, do not model the sources of such externalities and limit themselves to state their positive impact on the cost function.

3.3 Spillovers and market power

Although we do not adopt a coordination games framework, it has been stressed above that there are several conceptual similarities between it and the approach of this dissertation. In particular, (production) externalities and market power are two key ingredients of our analysis as well. We need, therefore, to be more precise about their nature and the role they are going to play. As it has been emphasized in the previous sections, our framework builds upon a specific source of complementarity between the workers experienced with a technology and the firm adopting that technology. The source of such complementarity lies in the existence of technology-induced spillovers — in the form of production externalities — affecting workers' wages, and the reason why these spillovers play a role resides in the imperfectly competitive (labor) market structure we are assuming.

3.3.1 Technology-induced spillovers: the link between wages and technology

The strength of our argument rests ultimately on the relevance of the labor market driven externalities originated by the adoption of superior technologies, that increase workers' (transferrable) knowledge — or better determines (requires) an upskilling of the labor force — and is ultimately responsible for the improvement of their outside options. Better alternatives, in turn, translate into an increase of wages that, in our framework, is driving the possibility of inefficient technology adoption.[8]

There are, thus, two points that have to been shown to corroborate our argument: the existence of a positive relationship between technological change and workers' skills; and that of a positive link between human capital and wages.[9]

The 20th-century experience of the USA, and of many other OECD countries, sheds light on both issues, confirming the importance of the mechanism we are focusing on. Returns to schooling have risen since the Seventies of the past century, generating a rapidly increasing skill premium. Over the same period, a substantial increase in wage and income inequality (even among similarly educated workers — the so called within group inequality) has been observed. As reported by Acemoglu (2003b), the college premium has increased by over 25% between 1979 and 1995. Moreover, in 1995, a worker in the 90th percentile of the wage distribution was earning 366% more than a worker at the 10 percentile, while the difference was 266% in 1971. Although several explanations have been proposed for the observed dynamics of the labor market and of the wage structure (the inequality within and between educational groups), there is a broad consensus that technical change is a major engine driving

[8] The idea of workers' mobility as a source of spillovers dates back to Arrow (1962). In a recent paper, D. Cooper (2001) discusses an innovation framework in which workers can take advantage of information acquired on the job by migrating to rival firms. Furthermore, Dalmazzo (2002) considers a setting — building upon Kremer's (1993) "O-ring" theory of production — in which firms adopting complex technologies end up paying higher wages to workers.

[9] We documented a host of technology driven spillover effects in Chapter 2. Several contributions stress the link between workers' human capital and their outside options. For a survey of these issues see Booth and Snower (1995). More generally, Acemoglu (1996) shows the existence of social increasing returns in human capital accumulation in presence of matching imperfections in the labor market and ex ante investment by firms and workers, emphasizing the importance of human capital externalities for development.

the dispersion in the distribution of wages.[10] Over the last sixty years, technological change appears to have strongly favored skilled (or, more generally, educated) workers over those unskilled, supporting a notion of *technology-skill complementarity* that is now widely accepted (besides the early contributions by Nelson and Phelps (1966) and Griliches (1969) see, among others, Autor, Krueger and Katz, 1998; Berman, Bound and Machin, 1998; Caselli, 1999; Allen, 2001; Aghion, 2002).[11] The supply of educated workers has greatly increased over the past decades, and yet returns to education have risen, suggesting an increase in the demand for skilled workers sufficient to overcome the increase in supply.[12] Furthermore, the skill-bias in technology adoption has accelerated since the late Seventies of the last century, possibly driven by the diffusion of information technologies even though it seems to be a more general feature common to many modern technologies (see, for example, Bartel and Lichtenberg, 1987 and 1991; Machin and van Reenen, 1998; and Autor, Krueger and Katz, 1998).[13]

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[10] For studies of the wage distribution and of earnings inequality — especially in relation to (skill-biased) technological change — see Goldin and Margo (1992), Katz and Murphy (1992), Galor and Tsiddon (1997), Acemoglu (1998, 1999, 2002b), Katz and Autor (1999), Krusell, Ohanian, Ríos-Rull and Violante (2000), Aghion, Howitt and Violante (2002) and Violante (2002), as well as Gottschalk and Joyce (1998) for cross-country comparisons, and Brown and Campbell (2002) for a survey on the impact of technological change on work and wages.

[11] The idea that technical progress is skill-biased must not be taken at face value. Several of the 19th-century advances in technology have indeed been skill-replacing, substituting skilled artisans with unskilled manual labor (see David, 1975). Whether technology will be skill-biased or not is ultimately related to the profitability of employing skilled versus unskilled workers.

[12] The increase in the demand for skills and inequality has an important explanatory variable in skill-biased technological change. However, it must be noted that other factors — like the changes in the organization of production (as reported, for instance, by Acemoglu, 1999; Caroli and van Reenen, 2002; and Bresnhan, Brynjolfsson and Hitt, 2002) or in labor market institutions (see, among others, Card, 1996; and Acemoglu, Aghion and Violante, 2002) — can be important as well.

[13] For theoretical underpinnings on the skill-bias in technology adoption, see the discussion in Chapter 2 (Section 2.3.3), and especially the references to Acemoglu (1998, 2002a).

The empirical evidence presented above — documenting the skill bias in technical progress and its strong positive impact on the wage structure — poses a subtle interpretation issue concerning the main ideas, outlined above, on which the next chapters of the dissertation build. On the one hand, it confirms the importance of the links between technology, skills and wages we are focusing on. On the other hand, however, it suggests that the technologies that are adopted (at least in advanced countries) are indeed those requiring more skills and paying higher wages. One might therefore be tempted to conclude that although the adoption of superior technologies determines an increase in the wages paid by firms, this effect must be of a second order, given that the observed pattern of technology adoption is strongly skill-biased. In other words, the increases in productivity associated to the adoption of a superior technology more than compensate the corresponding increases in wages, so that firms should always adopt the frontier technology. Otherwise, for example, we should observe the adoption of technologies complementing unskilled workers as it has been for most of the 19th-century. This conclusion, however, reflects the observed characteristics of technical change, while we focus on the determinants behind the decision of a firm to adopt a superior technology (and indirectly on the speed of the diffusion process). The interactions we suggest between technology and wages might well be responsible for delaying the adoption of specific technologies (and the speed of their diffusion) — a feature common to almost all technologies as we have shown in Chapter 2 — and nonetheless technical progress can remain skill biased. In other words, we focus on the mechanics of adoption (i.e. on the choice problem faced by the adopter) and not on the overall characteristics of the resulting technical progress.

3.3.2 The role of market power

Market structure is the second building block of our framework and plays a crucial role in determining the final impact of the interactions between workers and firm. The improvement of workers' outside options can translate into an increase in wages only disposing of the assumption of a perfectly competitive labor market. Workers must have bargaining power in the wage determination process — which implies an imperfectly competitive labor market — to be able to "cash" their better alternatives. In the absence of such market power, the firm would pay workers at their marginal productivity internalizing all rents arising from the adoption of a superior technology.

Labor market power is, however, still not enough for inducing the adoption of inferior technologies. No inefficiencies would , in fact, be observed if firms are able to transfer the increase in wages on the price of their final products. In this case, they would remain able to appropriate all the benefits associated to the adoption of a superior technology by transferring the increases in the cost of labor to final consumers. In other words, a combination of perfectly competitive goods markets, i.e. price takers firms, and of monopolistic factor markets is the ideal setting for technology-induced spillovers to have an impact on wages, and for them, in turn, to affect firms' technology choices. It is worth observing that the assumption of perfect competition in the goods market can be — to some extent — relaxed, without loosing much in terms of results, although this conjecture will not be developed further in the dissertation.[14] As far as firms do not have the ability (for a host of possible reasons: limits to their price making ability, economic regulations, etc.) to transfer the whole increase in costs on the price of the final good, the increase in

[14] Throughout the dissertation we will maintain the assumption of perfectly competitive product markets.

wages can still have a distortionary impact on technology choices. The absence of perfect competition in the labor market is, however, fundamental to the argument. The distortionary "transmission mechanism" between spillovers, wages and technology would be lost under the assumption of price taking behavior in the labor market, which would cancel the impact of spillovers on wages and, consequently, the source of inefficiencies in the choice of technology.

3.4 The efficiency wage framework

From the above discussion, it emerges quite clearly that the adoption of a superior technology can be substantially affected by the existence of strategic interactions (complementarities) stemming from the presence of technology-induced externalities and market power. Strangely enough, however, many theoretical contributions dealing with technology adoption still dispose of the role of the strategic interactions arising in the labor market, often focusing on perfectly competitive environments and representative agent frameworks.

We depart from this assumption. The basic structure of the models we will work with — in order to study the interactions between the decisions of a firm to adopt a technology and workers' outside options (wages) — builds upon the efficiency wage setting formulated by Shapiro and Stiglitz (1984).[15] As we will stress in the next chapters, such framework provides a natural way to model the relationships between technology, outside options and wages by means of workers' individual rationality and incentive compatibility constraints. In this respect, it proves to be a suitable setting to investigate technology adoption problems where the

[15] More generally, we will use a simple principal-agent approach following the contract theory literature. For a general textbook treatment see, among others, Macho-Stadler and Pérez-Castrillo (1997), Salanié (1997), and Laffont and Martimort (2002).

main restraints to the firm's choices about technology pass through their impact on wages.

It is therefore worth to delve into the details of a simplified static reformulation of the Shapiro and Stiglitz's theory we will use as the backbone for our models.

3.4.1 A reformulation of the efficiency wage model by Shapiro and Stiglitz (1984)

Shapiro and Stiglitz focus on the informational asymmetries arising in the relationship between employers and employees to explain involuntary unemployment as an equilibrium phenomenon. This form of unemployment stems from the inability of employers to costlessly monitor the effort exerted by workers. In a perfectly competitive framework, in which all employees receive the market wage and there is no unemployment, if a worker is caught shirking she can be fired, but she suffers no penalty for her conduct since she will be immediately re-hired. Thus, with imperfect monitoring, workers have an incentive to shirk. If a firm wants to induce workers not to shirk, it must pay more than the market wage, so that if a worker is fired she suffers a punishment. Since all firms will raise their wages to induce no-shirking, labor demand will decrease and unemployment will emerge. The presence of involuntary unemployment (job rationing) in equilibrium works as a discipline device, making sure that a fired shirker is not able to immediately find another job.

The Shapiro and Stiglitz model studies a simple general equilibrium economy characterized by significant principal-agents problems, where all the emphasis is on incentive effects. While the original model is set in continuous time (with infinitely lived agents), we simplify and reformulate it in a static framework, in the spirit of the models we will develop later in the dissertation.

The economy is populated by $\bar{N}$ identical workers (so that being fired carries no stigma) characterized by the individual utility function $U(w, e)$, where w denotes the wage received and e the level of effort exerted. All workers are assumed to be risk-neutral and the utility function is separable, so that — after normalization — $U(w, e) = w - e$. All workers can provide two levels of effort only: a minimal one ($e = 0$) or a fixed positive one ($e > 0$). When unemployed a worker exerts no effort and receives unemployment benefits $\bar{w} > 0$. When caught shirking a worker is fired, which turns out to be the firm's optimal policy in equilibrium. Differently from Shapiro and Stiglitz's original model, however, we do not allow for the possibility that a worker separates from her job for exogenous reasons.[16]

Each worker maximizes her individual utility by choosing the level of effort to exert. If she does not shirk, she retains her job and gets a wage w. If shirking, there is a positive probability c that she is caught, in which case she is fired and enters the unemployment pool. The worker decides whether to shirk or not by comparing the utility she gets from shirking with that from non shirking. Denoting with V^{ns}, V^{s} and V_u the utility levels of a non shirker, of a shirker and of an unemployed, respectively, they are

$$V^{ns} = w - e \tag{3.1}$$

$$V^{s} = (1 - c)\, w + cV_u. \tag{3.2}$$

The worker does not shirk if and only if $V^{ns} \geq V^{s}$, i.e. if and only if

$$w \geq \frac{e}{c} + V_u \equiv \hat{w}, \tag{3.3}$$

[16] The introduction of a turnover rate affects the rate at which workers are hired out of the unemployment pool and hence their utility level when unemployed that, in turn, affects the no-shirking constraints faced by other firms. Due to this externality, firms' choice of wage packages will not be optimal.

where V_u will be defined in Equation (3.5). Equation (3.3) has been labeled by Shapiro and Stiglitz as *no-shirking condition (NSC)* and makes clear that a worker has an incentive not to shirk only if there is a penalty with being unemployed.[17] It is immediate to notice that the critical wage $\hat{w}$ that the firm must pay to satisfy the NSC is increasing in the level of effort required and in the utility when unemployed, and decreasing in the probability of being detected shirking.

There are M $(i = 1, ..., M)$ identical firms in the economy, each of them characterized by a production function $Q_i = \phi(N_i)$, generating an aggregate production function $Q = \Phi(N)$, where

$$\Phi(N) := \max_{\left\{N_i \mid \sum_i N_i = N\right\}} \sum_i \phi(N_i). \tag{3.4}$$

We assume that $\Phi'(N) > e$, so that full employment is efficient. N_i denotes firm i's effective labor force. Each non-shirker worker contributes one unit of effective labor; shirkers contribute nothing. The monitoring technology of firms (c) is given exogenously and it is imperfect, in that firms can not monitor effort by observing output.

Firms compete in offering wage packages — consisting of a wage w and of unemployment benefits $\bar{w}$ — satisfying the NSC constraint. As for unemployment benefits, each firm has an incentive to make them as small as possible. This is immediate from Equation (3.3): an increase in $\bar{w}$ amounts to an increase in V_u, which determines an increase in the wage needed to satisfy the NSC. Moreover, since there will be equilibrium unemployment, firms have no difficulties in hiring the labor they need and thus reduce $\bar{w}$ as much as possible, until its minimum legal level if any. Concerning w, each firm offers a wage just sufficient to induce a worker to exert the desired level of effort, meeting the NSC with equality, i.e.

[17] The NSC constraint embodies both the individual rationality (or participation) and the incentive compatibility constraints encountered in the standard formulation of the principal-agent literature. We will often adopt this terminology in the models developed in the next chapters of the dissertation.

$w = \hat{w}$. Each firm's labor demand follows by equating this wage rate with the marginal product of labor ($\phi'(N_i) = \hat{w}$), so that the aggregate inverse labor demand is $\Phi'(N) = \hat{w}$.

Each individual firm's behavior is determined by the utility of an unemployed worker (labeled as *reservation utility*), V_u, that is the market variable affecting the wage any firm must pay in order to induce non-shirking behavior. The equilibrium level of V_u depends in turn on the probability that an unemployed worker can find a job (the aggregate job acquisition rate), which we denote with a. Formally, we have

$$V_u = (1-a)\,\bar{w} + a\bar{U}, \tag{3.5}$$

where $\bar{U}$ denotes the utility associated to the outside options — i.e. to the wage offers (net of the disutility of effort) a worker receives if employed by another firm — available to the worker. Substituting Equation (3.5) for V_u into the NSC (3.3), we get what Shapiro and Stiglitz call the *aggregate NSC*

$$w \geq \frac{e}{c} + (1-a)\,\bar{w} + a\bar{U}. \tag{3.6}$$

Since all firms are identical, at a symmetric equilibrium they will all offer a wage satisfying the aggregate NSC and therefore $\bar{U} = w$, so that Equation (3.6) can be rewritten as

$$w \geq \frac{e}{c}\frac{1}{1-a} + \bar{w}. \tag{3.7}$$

Finally, by letting $a = 1 - u$ — where u denotes the unemployment rate ($u = \left(\bar{N} - N\right)/\bar{N}$), the constraint (3.7) becomes

$$w \geq \frac{e}{c}\frac{1}{u} + \bar{w} \equiv \hat{w}. \tag{3.8}$$

By inspection of Equation (3.8) we can see that the threshold wage satisfying the aggregate NSC is increasing in the level of effort and in the unemployment benefits, and decreasing in the monitoring technology

c and in the unemployment rate u.[18] Let us examine these properties in turn. On the one hand, the higher the unemployment rate, the lower the job acquisition rate and, hence, the higher the punishment associated with being fired, so that a smaller wage is required to induce non-shirking. Similarly, a better monitoring technology (higher c) increases the probability that a shirker is caught, reducing the wage the firm must pay.[19] On the other hand, the higher the unemployment benefits, the higher the utility of an unemployed worker and, thus, the lower the punishment of being unemployed, rendering bigger the wage required to induce workers not to shirk. Finally, a rise in the level of effort increases workers' disutility from working and, therefore, increases the wage the firm must pay to induce non-shirking behavior.

Moreover, and most importantly, it is immediate to observe that the NSC is inconsistent with full employment. If $N = \bar{N}$, $1/u \to +\infty$, and all shirking workers would be hired again immediately. This eliminates the punishment associated with being fired and workers have an incentive to shirk.

Equilibrium occurs when it is optimal for all firms — taking as given wages and employment levels at other firms — to offer the going wage instead of a different one. The individual firm, being small, takes the aggregate unemployment rate (and thus the aggregate job acquisition rate) as given and offers (at least) the wage $\hat{w}$. The firm's labor demand determines the number of workers employed by each firm. The equilibrium

[18] Note that, from the aggregate NSC (3.8) with equality, it is immediate to derive the inverse aggregate labor supply, i.e.

$$N = \bar{N}\left(1 - \frac{e}{c\,(\hat{w} - \bar{w})}\right).$$

[19] Shapiro and Stiglitz consider also the case in which monitoring is endogenous, so that employees can trade off a stricter monitoring (higher c) with higher wages as methods of discipline. By increasing wages, employment is reduced and workers have less incentives to shirk. This allows firms to save resources on monitoring. In general however, due to the externalities between firms, monitoring intensities will not be optimal.

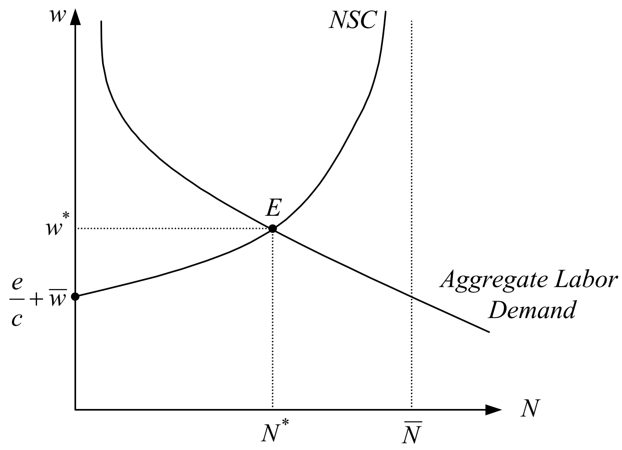

FIGURE 3.1. Market equilibrium

wage and employment levels (w^*, N^*), depicted in Figure 3.1, [20] are then defined by the intersection of the aggregate NSC (3.8) — substituting for the traditional labor supply locus — with the aggregate labor demand, i.e.

$$\Phi'(N) = \frac{e}{c}\frac{\bar{N}}{\bar{N} - N} + \bar{w}, \tag{3.9}$$

where we have taken into account the definition of u. No firm has an incentive to offer a wage higher than w^*, as at this wage workers are exerting the desired level of effort (and they have no incentives to shirk) and the firm can hire all the labor it needs. At the same time, no firm offers a wage lower than this level, because it would induce shirking behavior on the side of workers. Equilibrium unemployment serves as an effective discipline mechanism in deterring shirking behavior and it is involuntary from the workers' point of view.[21] They would work for the firm at a lower wage, but their promise not to shirk is not credible.

[20] All figures illustrating the model are drawn for a decreasing returns to scale aggregate production function.

[21] As Shapiro and Stiglitz (1984) themselves put it, there might be other discipline devices that can be effective under specific circumstances, based for instance on the heterogeneity of workers (so that fired workers would loose their reputation if fired), on the existence of costs imposed on dismissed workers (like the loss of specific human capital), or on the design of performance bonds.

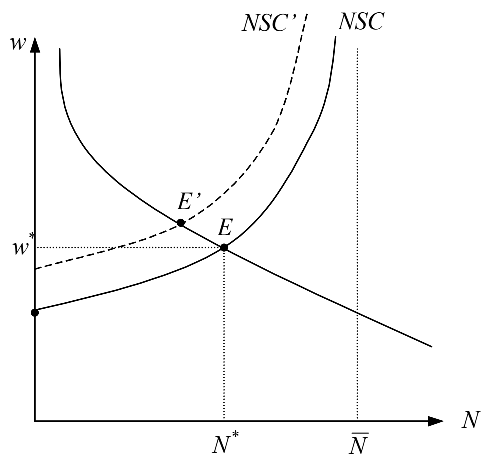

FIGURE 3.2. Comparative statics

Firms' inability to perfectly monitor the effort of their employees is thus the cause of equilibrium unemployment.

The equilibrium condition (3.9) allows for comparative statics exercises focusing on the NSC (right-hand side of Equation (3.9)). A decrease in the monitoring technology c, an increase in the effort e or in the unemployment benefits $\bar{w}$ imply, at any given level of employment, an increase in the wage required to induce non-shirking behavior. As represented in Figure 3.2, the NSC curve shifts upwards while the labor demand curve is unaffected, which determines an increase in the equilibrium wage and in the level of unemployment.[22]

It is easy to show that the unemployment equilibrium described above is not Pareto optimal. Assume that firms' ownership is equally distributed among the $\bar{N}$ workers. A social planner maximizes the representative

[22] The impact of $\bar{w}$ is stronger in the original Shapiro and Stiglitz's model, where changes in the unemployment benefits affect labor demand as well. In this sense, their model provides a possible explanation for wage sluggishness. Due to the NSC, following an inward shift of the labor demand schedule, wages can not fall enough to compensate for the decrease in labor demand. Wage cuts will take place only after the unemployment pool starts growing.

worker's utility subject to the NSC and to the resource constraint:

$$\begin{cases} \max\limits_{w,\bar{w},N} & (w-e)\,N+\bar{w}\left(\bar{N}-N\right) \\ s.t. & w \geq \frac{e}{c}\frac{\bar{N}}{\bar{N}-N}+\bar{w} \\ & wN+\bar{w}\left(\bar{N}-N\right) \leq \Phi\left(N\right) \\ & \bar{w} \geq 0, \end{cases}, \tag{3.10}$$

where the first constraint is the NSC and the second one the feasibility constraint.

From the assumption of workers' risk neutrality it follows that unemployment benefits are to be set at their minimum acceptable level, i.e. $\bar{w}=0$ (or the legal minimum).[23] Problem (3.10) simplifies to

$$\begin{cases} \max\limits_{w,\bar{w},N} & (w-e)\,N \\ s.t. & w \geq \frac{e}{c}\frac{\bar{N}}{\bar{N}-N} \\ & wN \leq \Phi\left(N\right) \end{cases}. \tag{3.11}$$

Figure 3.3 illustrates the social optimum and compares it with the market solution. Note that, as long as $\Phi'(N) > e$, indifference curves are steeper than the average product curve and thus the social optimum (w^{**}, N^{**}) occurs at the intersection between the NSC and the average product locus. The social optimum implies both higher wage and employment levels than the market equilibrium (occurring at the intersection between the NSC and the marginal product of labor locus), that is optimal only in the constant returns to scale case in which $\Phi'(N) = \Phi(N)/N$. Intuitively, the inefficiency of the market equilibrium stems from the fact

[23] By differentiating the Lagrangean corresponding to Problem (3.10) with respect to w and $\bar{w}$ one gets

$$\mathcal{L}_w = N+\lambda-\mu N \leq 0 \qquad = 0 \text{ if } w>0$$

and

$$\mathcal{L}_{\bar{w}} = \bar{N}-N-\lambda-\mu\left(\bar{N}-N\right) \leq 0 \qquad = 0 \text{ if } \bar{w}>0,$$

where λ and μ are the Lagrangean coefficients associated to the NSC and the feasibility constraint, respectively. By the NSC it is $w>0$, and hence it must be $\mathcal{L}_w = 0$. Since $\lambda > 0$, $\mu > 1$. This implies $\mathcal{L}_{\bar{w}} < 0$ and thus $\bar{w}=0$. Notice that the optimality of $\bar{w}=0$ would not carry over under workers' risk aversion if they can be separated from their jobs for exogenous reasons. The market equilibrium, however, would always be characterized by $\bar{w}=0$ or the legal minimum. This might provide a rationale for mandatory minimum benefit levels.

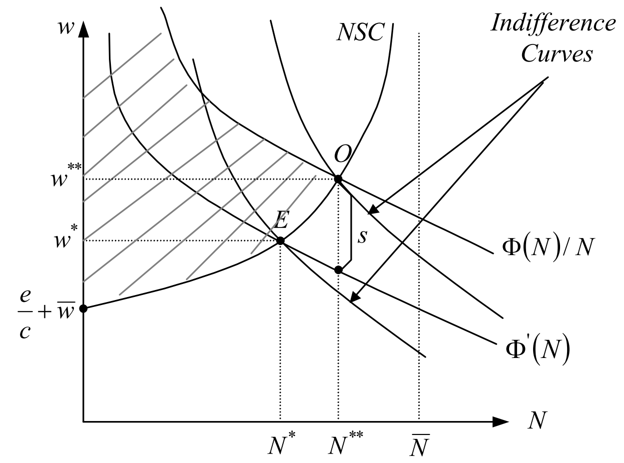

FIGURE 3.3. Social optimum and market equilibrium

that firms perceive a private cost for employing an additional worker (w) that is higher than the social cost (e), thus employing too few workers. Each firm fails to internalize its impact on the monitoring and wages that the other firms have to sustain to induce non-shirking behavior of workers.[24]

As emphasized by Shapiro and Stiglitz, the "natural" (market equilibrium) rate of unemployment is too high and hence there is a scope for government intervention. The most direct instruments available to achieve Pareto improvements in this setting are wage subsidies financed by means of a tax on profits, that are equivalent to the introduction of a tax on unemployment reducing the incentives to shirk. As shown in Figure 3.3, a Pareto efficient allocation can be reached by taxing away all profits and introducing a wage subsidy s. It is interesting to note that such a policy would not lead to Pareto improvements if the ownership of the firms is not in the hand of workers. A wage subsidy financed via

[24] Firms also fail to internalize the fact that hiring a new worker they are reducing the unemployment pool, thus making less severe the threat associated with being fired. This effect moves in the opposite direction with respect to the previous one, which however dominates. As observed by Shapiro and Stiglitz, this result does not carry over to more general models.

profit taxation would in fact worsen the position of firms' shareholders. The Pareto optimality of the equilibrium depends then on the distribution of wealth.

3.5 Summary

This chapter investigated the main issues and outlined the formal framework that constitute the backbone for the models that will be developed in the next chapters. We discussed the conceptual similarities of our externality driven approach with the literature on strategic complementarities (and coordination games), highlighting the existence of strategic interactions between a firm's choice to adopt a technology and the outside options available to the workers operating that technology. The sources of complementarity lie both in the existence of technology-induced spillovers (externalities) originating from the strategic interactions between firms and workers and in the presence of imperfect competition in the labor market.

We stressed how technology-induced externalities, combined with market power, determine a positive and increasing relationship between technology and wages. The role played by imperfect competition (the presence of market power) in the labor market is crucial in this respect, providing for a "transmission mechanism" between technology adoption and wages. In particular, we emphasized what would be lost by studying technology adoption in a perfectly competitive framework, stressing that under the assumption of price taking behavior in the labor market, there is no way for the strategic interaction between workers and firms — stemming from the technology-induced production externalities — to affect wages and, hence, firms' choice of technology.

The relevance of our argument as a possible engine of technology adoption rests ultimately on the actual importance of the spillovers effects (externalities) linking the choice of technology to the wage structure. By borrowing from the literature on the relationships between technical progress, wages and inequality, we documented a robust empirical evidence confirming the existence of a direct causal relationship between (skill-biased) technical change and the wage distribution. Furthermore, we reported on the evidence of a positive and accelerating skill premium induced by technology for the past several decades, which supports the view of an increasing relationship between technology adoption and wages.

Finally, the last part of the chapter formalized a static reformulation of the efficiency wage framework *à la* Shapiro and Stiglitz (1984) — constituting the backbone for the technology adoption models that will be discussed in the remaining of the dissertation —, working out its comparative statics and welfare implications. As it will become clear in the next chapter, this setup allows us to model both the presence of market power in the labor market — providing a framework for the formalization of the wage setting process according to the standard efficiency wages argument — and the link between firms' technology choices and workers' outside options, by making endogenous their outside options (i.e. their participation or individual rationality constraint) with respect to the firm's technology.

4

Technology Adoption and Efficiency Wages: A Partial Equilibrium Model

4.1 Introduction

This chapter discusses technology adoption by developing the ideas and building on the framework outlined in Chapter 3. Our basic underlying question is that of investigating why many firms choose to use inferior technologies even when better ones are widely available. In Chapter 2 we have emphasized that inefficient technology adoption seems to be a particularly important problem for firms operating in less-developed countries. As noticed there, the empirical literature supports the view that monopsonistic power in the factor markets is much more diffused in poor (and technologically under-developed) countries than it is in rich and developed countries. Such a view is definitely not new. It dates back to the Classics, being central both in A. Smith's and A. Marshall's thought, and it often resurfaces in the debate. It seems, therefore, natural to investigate what are the relationships between market power and technology adoption processes that impede the adoption of superior technologies instead of favoring it.

To restate our main claim: the presence of market power in the labor market can slow down the adoption of superior technologies, and thus technical progress, driving instead the adoption of inefficient technologies, even in the absence of coalitions of workers or forms of coordination.[1]

In this chapter we develop a partial equilibrium model studying a small economy, characterized by the presence of a self-employment sector, that we label as subsistence sector, and one industry, in which operates a price taker firm, selling its good on the international market. However, the labor market is monopsonistic and, given technology, labor is the only input of the production function. For simplicity, we assume that it is impossible for other firms to enter the industry. This impossibility can be due to institutional constraints or market imperfections (e.g. the distribution of property rights, or the presence of financial markets' imperfections), as well as to the absence of infrastructures or the relevance of political variables (like the presence of political instability or dictatorships), which make the entry of competitors impossible or unprofitable. This implies, in particular, that workers can not transform in entrepreneurs strating new firms even when the adoption costs of technology are nil. Workers can therefore be in one of two situations only: either they are employed by the firm, or they are unemployed (since there are not other employers available). When unemployed, workers receive their subsistence means from the subsistence sector, that is here assumed as a shortcut to model workers' outside options.[2]

We focus on the decision of the firm to adopt a superior technology. On the one hand, assuming that the introduction of a new technology does

[1] The latter are indeed the main factors inducing inefficient adoption in the Parente and Prescott's (1999) framework discussed in Chapter 2.

[2] In a more general setting, one can encompass a wide variety of possible outside options: employment at other firms, starting a new firm, and so on. we dispose of these extensions as they are not central to our argument.

not affect the demand for the produced good, the firm should observe an increase in its profits. On the other hand, the adoption of a superior technology has the consequence that employed workers can “learn” the technology just by using it. In other words, its adoption induces an increase in the level of human capital of employed workers: for instance, through some sort of learning process, that we assume to be instantaneous for simplicity. As anticipated in Chapter 3, as far as this learning process increases the level of workers’ transferrable human capital, it seems natural to assume that workers will be able to put at work the increase in their human capital in the subsistence sector, both using it directly or transmitting it to unemployed workers. The improvement in workers’ human capital, in turn, increases the productivity of workers in the subsistence sector and thus their reservation wages or, in a more general framework, their bargaining power, for example, through the organization in unions. In other words, the adoption of a superior technology generates spillover effects, which increase the reservation utility of workers. As stressed both in Chapter 2 and in Chapter 3, the impact of such spillovers on wages is well documented by the empirical literature, showing that the knowledge of a technology — and the skills to implement it — are very costly to produce but very easy to reproduce, and that firms are typically unable to appropriate all the benefits deriving from the technological innovations they introduce.

A firm needs, therefore, to offer higher wages to workers, if it wants them to accept its offer and exert the desired effort once employed. The associated increase in costs can be enough to induce the firm not to adopt a superior technology. Obviously, if both the firm and the workers are perfectly informed about the advantages and the costs associated to the adoption, then they can design bargaining procedures to allocate and distribute the net gains from the adoption of a better technology. However, workers have an incentive to bind themselves in a credible way to the agreements signed with the firm only if the wages they receive are high enough. Otherwise, whatever the structure of the agreement, they will try to take advantage from the available outside options.

From a modeling perspective, as anticipated in Chapter 3, the formal structure of our partial equilibrium economy resembles closely that of a uniperiodal reformulation of the efficiency wage model by Shapiro and Stiglitz (1984), outlined in Section 3.4.1 of Chapter 3. The main novelty of our model economy with respect to the one by Shapiro and Stiglitz is that, here, the participation constraint of workers becomes endogenous in the firm's choice of technology — with workers' reservation utility increasing in the firm's choice of technology — and, therefore, it can not be taken as automatically satisfied by assumption. As it will become clear in the next sections, it is exactly this endogeneity to determine the possibility of inefficient technology adoption.

The chapter is organized as follows. Section 4.2 characterizes the labor market and studies the workers' decision problem. Section 4.3 focuses on the firm's profit maximization problem and derives the result of inefficient technology adoption. Section 4.4 investigates labor market equilibrium, determining the equilibrium levels of employment and wage. Finally, in Section 4.5 all the results of the chapter are worked out for a Cobb-Douglas economy, that is subsequently used as a benchmark for comparative statics exercises. A summary of results and some specific extensions are presented in Section 4.6.

4.2 The workers

There are $\bar{N}$ identical consumers/workers and, at any point in time, each of them can be either employed by the firm or unemployed, in which case we assume that she is self-employed in the subsistence sector of the economy

Each worker supplies one unit of labor, receives positive utility from consumption and finds it costly to exert effort. We assume that the instantaneous utility function is separable and that workers are risk neutral, i.e.

$$U(w, e, T) = w - v(e) + \gamma\pi(N, T), \qquad (4.1)$$

where N denotes the number of workers employed by the firm, T is the technology it adopts, w is the wage paid, $v(e)$ is a function capturing the disutility of effort and $\gamma\pi(N, T)$ is the quota of the firm's profits going to each worker.[3] Assuming that the firm is owned by a benevolent social planner and that profits are equally distributed to all agents in the economy (or, which is the same, that the firm is a corporation equally owned by all agents in the economy), it is $\gamma = 1/\bar{N}$.[4] We will maintain this assumption throughout the dissertation, coming back to its implications in Chapter 5 (Section 5.2).

As in Shapiro and Stiglitz (1984), we assume for simplicity that the disutility of effort can take only one of two values $v(0) = 0$, when the worker exerts no effort, and $v(e) = e > 0$, when the worker exerts the level of effort required by the firm, i.e. when she does not shirk.[5] Each worker not exerting effort while working for the firm is subject to a probability c, $0 \leq c \leq 1$, of being caught shirking, in which case she is fired. We assume that the probability c — representing the firm's monitor-

[3] To be more precise, indicating individual consumption with x, each consumer faces the decision problem

$$\begin{cases} \max\limits_{x,e} & x - v(e) \\ s.t. & x \leq w + \gamma\pi(N, T) \end{cases},$$

form which it is appearent that one can immediately write (4.1) without loss of generality.

[4] This is only one of many possible profit distribution schemes, but it has the advantage of making possible direct comparisons between the firm problem and the planner problem, which will be introduced later.

[5] The assumption that the disutility of effort is equal to the level of effort exerted itself is without loss of generality in the present framework; e is treated as an exogenous parameter mainly on grounds of analytical simplicity, and such an assumption will be maintained throughout the dissertation. We will come back to the role of e in Chapter 5 (Section 5.5.2).

ing technology — is given exogenously. Such an assumption could be relaxed by letting c to be a function of the technology adopted by the firm. However, if it is evident that there might be a relationship between the technology operated by the firm and its monitoring technology (c), the sign of such relationship is in general ambiguous.[6] Once a worker is fired, the probability to be re-hired determines the length of the unemployment spell. Notice that whenever new technologies are labor saving, when a superior technology is adopted the number of employed workers tends to diminish (given output). It becomes therefore easier for the firm to hire the needed labor force from the pool of unemployed, and more difficult for a fired worker to be re-hired. In order to ease the exposition and to further highlight the impact of the firm's technology choices on wages, we make the assumption that

Assumption 4.1 *The probability that a worker is hired again by the firm once fired is equal to zero.*

Assuming a job acquisition rate equal to zero for fired workers amounts to rendering most severe the punishment associated with shirking, thus lowering the wage required to induce non shirking behavior. Finally, we also exclude the possibility that a worker can separate from her job for exogenous reasons (i.e. when not shirking). Our conclusions would remain unaffected by the introduction of a positive probability to leave the job, along the lines discussed in Shapiro and Stiglitz (1984).

Notice that we slightly abuse terminology as we refer to unemployment and self-employment as synonymies. In a strict sense there are no unemployed agents in our framework since all workers that are not employed by

[6] We will come back to this point on Chapter 5. Notice also that, besides the relationship between monitoring and technology, there are other dimensions with respect to which c could be made endogenous to the model. For instance, as noticed in Chapter 3 (Section 3.4.1), Shapiro and Stiglitz (1984) discuss how firms and workers can exchange stricter monitoring (costly for the firm) with higher wages.

the firm are in the subsistence (self-employment) sector of the economy, which we take as a shortcut to model the workers' outside options. This is different with respect to Shapiro and Stiglitz's setting, where outside options are modeled by means of the probability to be hired by one of the identical (and in finite number) firms populating the economy once unemployed. This probability is, in general, lower than one so that workers can remain unemployed, in the proper sense, receiving an exogenously set unemployment benefit. This abuse of notation is, however, innocuous as it will be apparent that, once we allow for it, all of Shapiro and Stiglitz's observations about involuntary unemployment go through.

If unemployed (self-employed) an individual obtains utility $\bar{U}(T)$ in the subsistence sector of the economy: a function of the technology adopted by the firm, on which we make the following assumption.

Assumption 4.2 $\bar{U}(T) \in C^2$, $\forall T \gg 0 : \bar{U}'(T) > 0$.

That is, we assume that the reservation utility is an increasing function of technology because of the positive spillover effects associated to technology adoption processes. In order to eliminate the possibility of heterogeneity between (skilled) employed and (unskilled) unemployed agents, we assume that once a superior technology has been introduced, its knowledge diffuses instantaneously. We could as well assume the presence of a union (or of institutional constraints) linking the firm's wage structure to the technology chosen and not to individual skills. If the firm does not have the opportunity to pay lower wages to the newly hired workers, the heterogeneity among skilled and unskilled workers disappears. Notice further that we assume that the firm's technology choice does not affect the decision of a worker to shirk or not to shirk. In a more sophisticated formulation, however, one could assume that a non-shirker worker can learn the technology faster and in a better way than a shirker, benefiting more of the spillover effects induced by the technology.

This would make shirking more costly, contributing to relax the incentive compatibility constraint.

Finally, although there are several possible explanations for the existence of a relationship between the firm's technology adoption decision and consumers' reservation utility (i.e., workers' outside options), in this chapter we take it as given. We will focus on the determinants of workers' outside options in Chapter 5, where we will introduce a general equilibrium model economy, by rendering fully endogenous the factors affecting the reservation utility. Here we only provide a qualitative argument, confirming that $U(w, e, T)$ and $\bar{U}(T)$ are modeled in a coherent way. We may think that both the disutility of effort (when an agent is employed by the firm and when unemployed) and the reservation utility are functions of agents' skills. Furthermore, it seems reasonable to assume that skills are increasing in the technology adopted by the firm, which allows us to write both the disutility of effort and the reservation utility as functions of technology. Since in our setting we assume that the disutility of effort can take only one of two values $(0, e)$, we do not need to model explicitly the relationship between technology and disutility of effort. Finally, since the reservation utility is increasing in skills, that in turn increase with technology, we can write directly $\bar{U}(.)$ as an increasing function of T.[7]

Workers maximize their utility by solving a decision problem with respect to the effort level. As in the Shapiro and Stiglitz model, they compare the levels of their expected utility when exerting effort and when not exerting effort. However, while the original Shapiro and Stiglitz model is set in continuous time, we can limit our attention to a static problem (as in our formulation of their model presented in Chapter 3, Section 3.4.1), given that we assume the probability to loose the job and the probability

[7] The analysis would not change if we allow for a generic disutility of effort as a function of technology, provided that we assume that the skill improvement associated to the adoption of superior technologies decreases the disutility of effort.

to be re-hired once fired being equal to zero. We denote with V_u, V^{ns} and V^s the utility of an unemployed, of a non shirker and of a shirker worker, respectively

$$V_u = \bar{U}(T) + \frac{1}{\bar{N}}\pi(N,T) \tag{4.2}$$

$$V^{ns} = w - e + \frac{1}{\bar{N}}\pi(N,T), \tag{4.3}$$

$$V^s = (1-c)w + (1-c)\frac{1}{\bar{N}}\pi(N,T) + cV_u. \tag{4.4}$$

Workers will not shirk if and only if

$$V^{ns} \geq V^s,$$

which, after some algebraic manipulations, leads to the no-shirking constraint (or, adopting the terminology of principal-agent theory, workers' incentive compatibility constraint)

$$w \geq \bar{U}(T) + \frac{1}{c}e, \tag{4.5}$$

that is

$$\frac{c}{1-c}[V^s - V_u] \geq e. \tag{4.6}$$

Constraint (4.6) highlights the fact that, in the absence of a credible punishment phase following shirking, all workers have an incentive to shirk: if $V^s = V_u$ Condition (4.6) can not be satisfied. It is also immediate to check that the individual rationality (participation constraint) of a non shirker worker — $V^{ns} \geq V_u$, that is $w \geq \bar{U}(T) + e$ — is implied by Condition (4.5).

In our model, the decision on the level of effort depends crucially on the technology adopted by the firm. Let

$$\hat{w}(T) := \bar{U}(T) + \frac{1}{c}e \tag{4.7}$$

denote the no-shirking wage, that satisfies the worker's individual rationality constraint as well. Workers do not shirk if the wage paid by the firm is at least equal to $\hat{w}(T)$, which is the minimum wage that must be paid in order to induce a worker to exert effort. It is straightforward to observe that $\hat{w}(T)$ is increasing in the utility of the unemployed worker. The latter, in turn, is increasing in the technology adopted by the firm, clarifying the role of the choice of technology in rendering endogenously binding the participation constraint of workers. As in Shapiro and Stiglitz original framework, $\hat{w}$ increases when the level of effort e exerted by a worker increases and when the probability c she is detected shirking decreases. The bigger c, the bigger $\frac{c}{1-c}$ and therefore the lower the premium, $(V^s - V_u)$, needed to induce a worker not to shirk.[8]

4.3 The firm

The production sector consists of one industry in which one firm only operates, that is price taker on the good market and price maker on the labor market.[9] We assume without loss of generality that the good's price is equal to one, so that the model is formulated in real terms. The firm's production function is $\Phi(N, T)$, where T is the technology adopted by the firm and N the labor input used when the adopted technology is T. A worker provides one unit of effective labor if she does not shirk, while her contribution to output is zero when she shirks.

---

[8]Notice that V^s is a function of c. By defining $\varphi(c) = V^s - \bar{U}(T)$ and by using De L'Hôpital's theorem we have:

$$\lim_{c \to 1} \frac{c}{1-c} \varphi(c) = w - V_u > 0,$$

and

$$\lim_{c \to 0} \frac{c}{1-c} \varphi(c) = 0 < e < w - V_u,$$

where the latter inequality follows directly from the individual rationality constraint by making use of (4.2). Thus, there must exist a value $\underline{c}$ such that if $c < \underline{c}$ the no-shirking constraint (4.6) is never satisfied, and if $c > \underline{c}$ it is always satisfied.

[9]The price of the good is set by the competition on the international markets in which the firm operates, and the latter takes it as exogenously given.

In this model, technology enters the production function exactly as capital in standard models. However, as already stressed in the previous chapters, it may be useful to think at technology in a broader sense, for example, extending its meaning to the firm's organizational processes or the management's characteristics. The following assumption is made.

Assumption 4.3 $\Phi(N,T) \in C^2$, $\forall (N,T) \gg 0 : \frac{\partial \Phi(N,T)}{\partial T} > 0$, $\frac{\partial \Phi(N,T)}{\partial N} > 0$ *and* $\frac{\partial^2 \Phi(N,T)}{\partial N^2} < 0$.

Given that labor is the only input in the production function besides technology, technological progress is labor saving — meaning that superior technologies increase the productivity of labor — whenever $\frac{\partial^2 \Phi(N,T)}{\partial N \partial T} > 0$.

The firm's problem amounts to decide what technology to adopt among those that are available, as defined by the closed interval $[0, T_{\max}]$, $T_{\max} > 0$, where they are indexed and ranked by their efficiency. That is, $T = 0$ denotes the worst technology and $T = T_{\max}$ the best one among those available. We assume, for simplicity, that there are no direct technology adoption costs and we do not model explicitly a market for technology. This seems to be without loss of generality given our purpose. In fact, the explicit introduction of a price and/or of a direct cost associated to the adoption of a superior technology would further reduce the incentives for the firm to adopt it, reinforcing the impact of spillovers. However, given the absence of adoption costs and/or of a price for technology, one might argue that workers themselves have an incentive to introduce a superior technology, as their reservation utility (i.e. outside options) is increasing in it. The implicit assumption here is that a technology can be introduced by the market sector firm only; so that workers can benefit from the technology only after it has been adopted by the firm.[10]

[10] A natural way to justify this assumption would be to argue that the choice of a technology entails costs (like those for experimenting among the available alternatives, or the price of the technology

4.3.1 The social planner problem

The benchmark to define the best available technology is given by the first best solution of a benevolent social planner's decision problem. We assume that the planner's objective function is an utilitaristic social welfare function, so that she maximizes the sum of the firm's profits and the utility of all employed and unemployed workers.[11] Therefore its problem can be written as:

$$\max_T \quad [\Phi(N^{ns}, T) - w(N^{ns} + (1-c)N^s) + (w-e)N^{ns} + \\ +w(1-c)N^s + cN^s\bar{U}(T) + (\bar{N} - N)\tilde{U}\Big], \tag{4.8}$$

where $N = N^{ns} + N^s$, and (N^{ns}, N^s) denote respectively the number of shirker and non-shirker workers at any point in time, and $\tilde{U}$ denotes the reservation utility of never-employed workers. We write N^{ns} instead of N in the production function to highlight the fact that only non-shirker workers contribute to production. By rearranging the terms, Problem 4.8 can be rewritten equivalently as

$$\max_T \quad \Phi(N^{ns}, T) + cN^s\bar{U}(T) - eN^{ns} + (\bar{N} - N)\tilde{U}. \tag{4.9}$$

The solution of Problem (4.9) is

$$\bar{T} := \arg\max_T \quad \left\{\Phi(N^{ns}, T) + (cN^s)\bar{U}(T) - eN^{ns} + (\bar{N} - N)\tilde{U}\right\}. \tag{4.10}$$

itself) that an individual can not bear, even in the presence of fairly efficient capital markets. Such justification is obviously at odds with the assumption of technology being a costless "input". One should instead, and more realistically, assume that there are positive adoption costs (and/or a positive price for technology). However, as our focus is on investigating the impact of technology induced spillovers/externalities, we keep such costs in the background, letting them artificially equal zero. Note, moreover, that besides being coherent with the empirical evidence (as stressed in Chapter 2), the assumption on the absence of direct adoption costs and instantaneous spread of (available) technological knowledge is quite common in the literature not focusing explicitly on such costs as the main engines behind technology adoption (see, among others, Zeira, 1998, and Basu and Weil, 1998). We will further come back to the implications of the absence of an adoption cost (or a price) for technology in Chapter 5 (Section 5.2.2).

[11] This is coherent with the profit distribution scheme introduced in Section 4.2.

Given that c, e, and $\tilde{U}$ are independent of the adopted technology, and since, for all N, $\Phi(N^{ns}, T)$ and $\bar{U}(T)$ are monotonically increasing in T, $\bar{T}$ is a constant function of N. Therefore, a benevolent social planner, whose objective is to maximize the social welfare function, adopts technology $T_{\max}$, i.e. $\bar{T} = T_{\max}$.

4.3.2 Technology adoption and labor demand

The firm's objective consists in the maximization of the profit function under the worker's no-shirking constraint, that, as it has been noticed above, satisfies the individual rationality constraint as well. Therefore, it solves the optimization problem:

$$\begin{cases} \max\limits_{N,T} & \Phi(N,T) - wN \\ s.t. & w = \bar{U}(T) + \frac{1}{c}e \end{cases}. \tag{4.11}$$

We will start concentrating on interior solutions, without taking into account the additional constraints $0 \leq N \leq \bar{N}$ and $0 \leq T \leq T_{\max}$.

Problem (4.11) can be solved in two steps. In the first one we maximize the profit function with respect to technology, given N, while in the second step, once the optimal technology as a function of N has been determined, we will solve the problem in N.

By substituting the participation and incentive compatibility constraint into the profit function and by maximizing it with respect to T, given N, we have

$$\max_{T} \quad \Phi(N,T) - \left(\bar{U}(T) + \frac{e}{c}\right) N. \tag{4.12}$$

The first order condition is

$$\frac{\partial \Phi(N, t^*(N))}{\partial T} - \bar{U}'(t^*(N))\, N = 0, \tag{4.13}$$

where the function $t^*(N)$ denotes the arg max of Problem (4.12). In order to guarantee the concavity of the objective function in T, we assume

Assumption 4.4 $\bar{U}''(T) > \frac{1}{N}\frac{\partial^2 \Phi(N,T)}{\partial T^2}$, $\forall T > 0$.

Assumption 4.4 requires that, for all T, the impact of changes in technology on the reservation utility is greater than the impact on the marginal productivity of technology for the firm.[12] It is straightforward to observe that the objective function is always concave when $\frac{\partial^2 \Phi(N,T)}{\partial T^2} < 0$.

Given the concavity of the objective function, the first order Condition (4.13) is both necessary and sufficient for a maximum of the firm's technology adoption choice, given N.

It is immediate to prove the following proposition showing that, under the assumptions we made on $\Phi(N,T)$ and $\bar{U}(T)$ and given that $\bar{T}$ is not a function of N, i.e. $\bar{T} = T_{\max}$, there exists one and only one technology (different from the maximal one) which satisfies Condition (4.13) and is a maximum of Problem (4.11).

Proposition 4.1 ***(Existence)*** *Let Assumptions 4.3 and 4.2 on $\Phi(N,T)$ and $\bar{U}(T)$ hold, and assume that, $\forall N \in \left[0, \bar{N}\right]$, the following boundary conditions*

(1) $\frac{1}{N}\frac{\partial \Phi(N,T)}{\partial T} \mid_{T=0} > \bar{U}'(T) \mid_{T=0}$,

(2) $\frac{1}{N}\frac{\partial \Phi(N,T)}{\partial T} \mid_{T=T_{MAX}} < \bar{U}'(T) \mid_{T=T_{MAX}}$,

hold. Then, $\forall$ N, there exist an interior solution $t^*(N)$, $0 < t^*(N) < T_{\max}$ to Problem (4.11).

(Uniqueness) *Under Assumption 4.4, the above solution $t^*(N)$ is unique.*

---

[12] By using the first order condition (4.13), it is easy to study the sign of $t^*(N)$. Applying the implicit function theorem we get:

$$\frac{dt^*(N)}{dN} = -\frac{\frac{\partial^2 \Phi(N,t^*(N))}{\partial T \partial N} - \bar{U}'(t^*(N))}{\frac{\partial^2 \Phi(N,t^*(N))}{\partial T^2} - \bar{U}''(t^*(N))N}.$$

Since, given the assumption on the concavity of the objective function, the denominator of the previous expression is always negative, the sign of $\frac{dt^*(N)}{dN}$ depends on the sign of the numerator. In particular, in case of labor-saving technological progress, both $\bar{U}'(t^*(N))$ and $\frac{\partial^2 \Phi(N,t^*(N))}{\partial T \partial N}$ are positive, and thus the numerator will be negative if $U'(t^*(N)) > \frac{\partial^2 \Phi(N,t^*(N))}{\partial T \partial N}$.

Proof. *(Existence)* Given the boundary Conditions (1) and (2), since both $\Phi(N,T)$ and $\bar{U}(T)$ are differentiable, existence follows by the intermediate value theorem.

(Uniqueness) Follows immediately by Assumption 4.4 guaranteeing the concavity of the objective function in T. ■

Notice that Assumption 4.4 is required to prove the uniqueness of the equilibrium only, while it plays no role for existence. Uniqueness, however, is not a central issue in our framework, that revolves around the existence of an internal solution showing the possibility of inefficient technology adoption. If there is more than one interior solution, one could simply select the "best" (i.e. the superior one) among them.[13]

Under the assumptions of Proposition 4.1, three possible cases can occur. When $\frac{\partial^2\Phi(N,T)}{\partial T^2} < 0$ and $\bar{U}''(T) > 0$ the conclusion stated by the proposition follows immediately from boundary Conditions (1) and (2). When $\frac{\partial^2\Phi(N,T)}{\partial T^2} > 0$ and $\bar{U}''(T) > 0$, both $\frac{\partial\Phi(N,T)}{\partial T}$ and $\bar{U}'(T)$ are increasing functions. By continuity and monotonicity, from Conditions (1) and (2), it follows that $\frac{\partial\Phi(N,T)}{\partial T}$ and $\bar{U}'(T)$ intersect in the interval $(0, T_{\max})$ and such intersection is unique under Assumption 4.4. Similarly when $\frac{\partial^2\Phi(N,T)}{\partial T^2} < 0$ and $\bar{U}''(T) < 0$ both $\frac{\partial\Phi(N,T)}{\partial T}$ and $\bar{U}'(T)$ are decreasing functions and existence follows, again by monotonicity and continuity, if the boundary Conditions (1) and (2) are satisfied, while uniqueness is guaranteed by Assumption 4.4. Figures 4.1, 4.2 and 4.3 provide a graphical representation of the logic behind Proposition 4.1.[14] It is straightforward to observe that whenever Conditions (1) and (2) are not satisfied it is possible to reach corner solutions in which the firm might choose the worst

[13] Dropping the uniqueness of the equilibrium could be of some interest in a framework characterized by the presence of competing firms, where it would allow to study the issue of firms' coordination in technology adoption, hence highlighting, for example, the working of standard setting processes.

[14] In these figures the functions $\frac{1}{N}\frac{\partial\Phi(N,T)}{\partial T}$ and $\bar{U}'(T)$ are represented as linear functions only for convenience. It needs not necessarily to be the case.

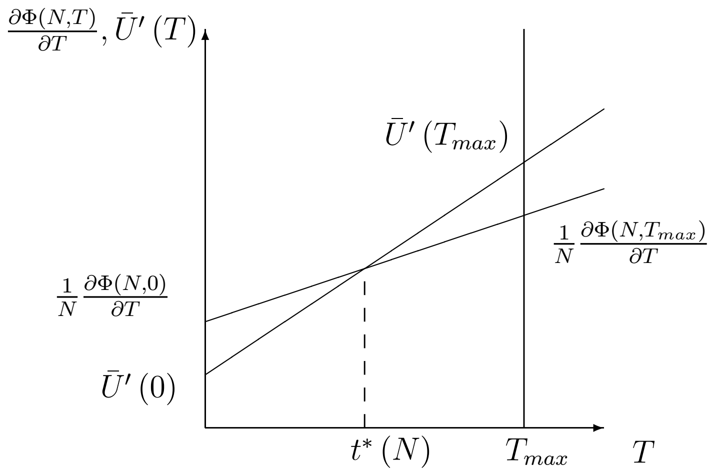

FIGURE 4.1. Determination of $t^*(N)$ when $\frac{\partial^2 \Phi(N,T)}{\partial T^2} > 0$ and $\bar{U}''(T) > 0$

technology available (in which case innovations are completely absent), as well as the best technology available (on the technological frontier) $T_{\max}$. In particular, the latter will always be the case if $\frac{\partial^2 \Phi(N,T)}{\partial T^2} > 0$ and $\bar{U}''(T) < 0$.

From an economic point of view, Condition (1) states that, when starting from very low technologies, the marginal increase in workers' reservation wage is lower than the increase in the marginal productivity of technology induced by the adoption of the better technology. This seems to be quite intuitive. Consider, as an example, the case of a firm that operates a form of large-scale agriculture in which there are barriers to entry induced by the allocation of property rights on the land. A superior technology with respect to traditional methods in which each worker is responsible for all the phases of cultivation can consist in a new technique requiring a worker to specialize in just one particular phase of the production process. Such technological upgrading would be nothing more than a better division of labor, similar to the one discussed by A. Smith. Quite obviously, all workers should be able to use both technologies and we can expect that the induced spillover effects benefiting workers are

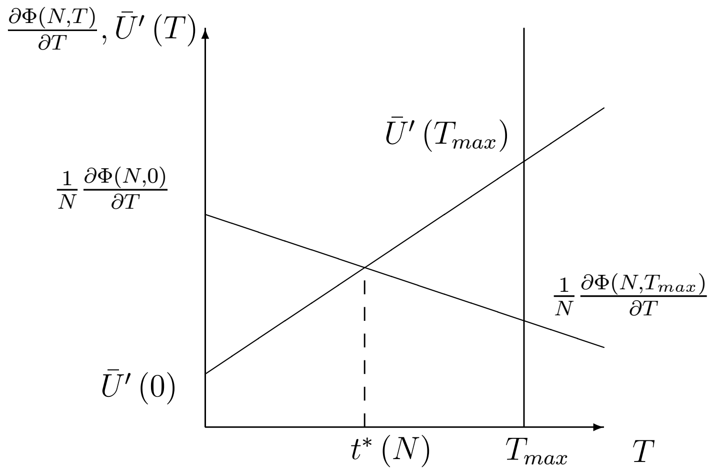

FIGURE 4.2. Determination of $t^*(N)$ when $\frac{\partial^2 F(N,T)}{\partial T^2} < 0$ and $\bar{U}''(T) > 0$

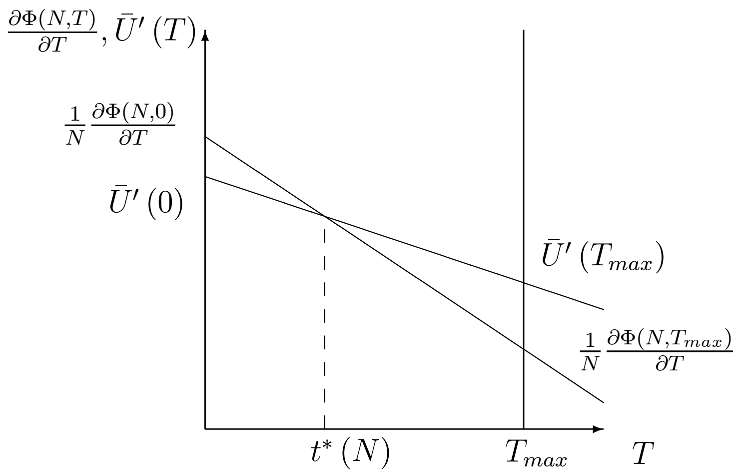

FIGURE 4.3. Determination of $t^*(N)$ when $\frac{\partial^2 \Phi(N,T)}{\partial T^2} < 0$ and $\bar{U}''(T) < 0$

not particularly significant. However the new division of labor can greatly improve the firm's profitability.

Condition (2) requires that exactly the opposite occurs in the case the best (i.e. highly ranked) technologies are adopted. Marginal productivity should be growing at a slower pace than the reservation utility of workers. In this case, spillover effects are so significant to induce the firm not to innovate. In the framework of the previous example, this may be the case of the adoption of technologies based on the genetic selection of seeds, which imply a great deal of human capital to be used, but do not require significant investment in fixed capital. This, in turn, implies that workers may be able to apply the knowledge they acquire even in the subsistence sector, thus increasing their reservation wage. Therefore, the marginal gain for workers (associated to the adoption of an advanced technology) culd be higher than the gain for the firm.

In the case in which superior technologies determine an increase in marginal productivity (depicted in Figure 4.1), that is $\frac{\partial\Phi^2(N,T)}{\partial T^2} > 0$, spillover effects are high enough for an inefficient technology to be adopted when Assumption 4.4 holds and boundary Conditions (1) and (2) in Proposition 4.1 are satisfied. The inefficiency result is thus driven by the importance of the spillover effects themselves. It is worth stressing once again that the channel through which spillover effects and monopolistic power on the labor market can block technological progress is a strategic one, that depends on the relationship between the reservation utility of workers and the technology adopted by the firm, via the technology-induced spillovers. Although the nature of these spillovers is not modeled explicitly here, as argued in Chapter 3, one might think they stem from the transferable human capital originating from the worker's ability to manage a certain technology. A worker's expertise with a technology is a cost for the firm, which the latter can not transfer on the workers themselves or on the good price (due to the price taking assumption). By learning a technology workers acquire better skills and increase their level of knowledge which, in turn, increase the value of their outside options (i.e. their utility level in the subsistence sector). Thus, on the one hand, the adoption of a superior technology increases the productivity of employed workers and the profits of the firm. On the other hand, it implies an increase in the cost of labor induced by the presence of spillovers related to the fact that workers learn (for convenience instantaneously) the new technology. This, in turn, implies an increase in their reservation utility, provided they can exploit their knowledge elsewhere, and consequently an increase of the wage the firm must offer in order to induce workers to accept its employment offer and to exert the required level of effort (as in the standard efficiency wage model). That is, the participation constraint of workers becomes endogenous in the technology choice. The adoption of a new technology can determine an increase in the wage sufficient to induce a profit-maximizing firm not to adopt the superior technology, in order to avoid the impact of induced spillovers on the cost of labor.

It is straightforward to show that, in the absence of technological spillovers and taking the price for the product to be given exogenously — as it is the case in a perfect competition setting — the firm would adopt the best technology available, $T_{\max}$, for any level of N. This follows immediately from the fact that the profit function is increasing in T, which is available at no cost. That is, our firm would behave as a benevolent social planner. Without technological spillovers, the firm would in fact be a price taker both on the product market and on the labor market. It would not take into account that its decision to adopt a new technology influences the reservation utility of workers and hence their wages (via its impact on their reservation wage and individual rationality constraint). In the absence of spillovers, the participation and incentive-compatibility constraints (i.e. $w = \bar{U}(T) + \frac{1}{c}e$) need still to be verified in equilibrium, but there is no longer a direct correlation between utility (wage) and technology. The technology adoption problem of the firm becomes therefore

$$\max_{T} \quad \Phi(N,T) - wN$$

and since $\Phi(N,T)$ is increasing both in T and N, for any N, it is

$$\arg\max_{T} \quad \{\Phi(N,T) - wN\} = T_{\max}.$$

This confirms once more that the possible adoption of inefficient technologies derives from the price making assumption and from the presence of workers' "bargaining" power in the labor market. These features are responsible for the emergence of the spillover effects that make the reservation utility and the wage of workers endogenous with respect to the technology. Through this channel, they influence the firm's decisions rendering the adoption of superior technologies more costly, and hence originating the inefficiency result.

4.4 Labor market equilibrium

Once the optimal technology $t^*(N)$ has been determined as a continuous function of N, we must check if, given t^*, there exists a N^* maximizing the firm's objective function. Since the profit function is continuous both in T and N and it is defined in a closed and bounded interval, given t^*, there must exist a value $N^* \leqq \bar{N}$, maximizing profit. By Proposition 4.1, we know that, at $N = N^*$, there exists a technology $t^*(N^*)$ which is away from the boundary even if N^* is on the boundary, i.e. $t^*(N^*) < \bar{T} = T_{\max}$.

We can now determine the equilibrium levels of employment and wage. The adopted technology, $t^*(N^*)$, determines immediately the equilibrium level of the wage, $w^* := \hat{w}(t^*(N^*))$, the firm must offer in order to induce workers to accept an offer and to exert the required level of effort. Moreover, the labor demand at an interior solution (i.e. $0 < N^* < \bar{N}$) determines the equilibrium level of employment in the industry; i.e. the number of workers employed given the equilibrium wage. Formally, given $t^*(N)$, the firm's maximization problem is

$$\max_{N} \quad \Phi(N, t^*(N)) - \hat{w}(t^*(N))\, N. \tag{4.14}$$

The number of workers employed in equilibrium, N^*, must satisfy the first order condition

$$\left(\frac{\partial \Phi(N^*, t^*(N^*))}{\partial N} + \frac{\partial \Phi(N^*, t^*(N^*))}{\partial T} \cdot \frac{dt^*(N^*)}{dN} \right) = \tag{4.15}$$

$$= \hat{w}(t^*(N^*)) + \frac{\partial \hat{w}(t^*(N^*))}{\partial T} \cdot \frac{dt^*(N^*)}{dN} N.$$

By observing that the first order Condition (4.13) in the technology adoption problem can be written as

$$\frac{\partial \Phi(N^*, t^*(N))}{\partial T} = \frac{\partial \hat{w}(t^*(N^*))}{\partial T} N,$$

we have:

$$\frac{\partial \Phi(N^*, t^*(N^*))}{\partial T} \cdot \frac{dt^*(N^*)}{dN} = \frac{\partial \hat{w}(t^*(N^*))}{\partial T} \cdot \frac{dt^*(N^*)}{dN} N.$$

Therefore, Condition (4.15) is satisfied whenever

$$\frac{\partial \Phi(N^*, t^*(N^*))}{\partial N} = \hat{w}(t^*(N^*)). \tag{4.16}$$

In order to determine N^*, it is therefore enough to guarantee that the equilibrium wage, given the adopted technology, is equal to the marginal productivity of labor.[15]

It is important to note that, as in Shapiro and Stiglitz model and for the same reasons, in our model it is impossible to reach a full employment equilibrium satisfying at the same time the participation and incentive constraints of workers, and thus there is involuntary unemployment in equilibrium. If, at $T^* := t^*(N^*)$, it is optimal for the firm to employ all

[15] It is a matter of standard algebra to solve for the equilibrium values of technology and employment for given functional forms. This is done in Section 4.5 for a Cobb-Douglas economy.

available labor force and there are no significant costs associated with being fired (loss of reputation, moving costs and so on), the threat to be fired and never re-hired by the firm is not a credible one and, thus, all workers would have an incentive to shirk. Assumption 4.1 establishes that the probability to be re-hired by the firm once fired is equal to 0. This assumption would be untenable at a full employment equilibrium. To better see the point, let the job acquisition rate for an unemployed worker to be greater than 0 and denote it with a, $0 < a \leq 1$. Indicate with $K \neq 0$, $0 < K < N$, the number of fired workers, i.e. the flow of workers per unit of time *into* the subsistence sector of the economy. The flow of unemployed toward the industry (i.e. *out* of subsistence) per unit of time is $a(\bar{N} - N + K)$. At a stationary state these flows must be equal, i.e.

$$a\left(\bar{N} - N + K\right) = K \Rightarrow a = \frac{K}{\left(\bar{N} - N + K\right)}.$$

Whenever $N \rightarrow \bar{N}$, it is $a = 1$; hence a fired worker would be immediately re-hired by the firm.

Only the presence of equilibrium unemployment makes the threat of firing credible. Therefore also in our model equilibrium unemployment constitutes a discipline device for workers.

At the equilibrium wage, $w^* = \hat{w}\left(T^*\right)$, the firm can hire all the workers it needs and the latter have an incentive to exert the required effort. There is no reason for the firm to offer wages higher than $\hat{w}\left(T^*\right)$ and of course there is no incentive to offer wages below $\hat{w}\left(T^*\right)$, because they would lead to a shirking behavior by workers.

Equilibrium unemployment is involuntary. Unemployed workers would not be employed by the firm even if they are willing to accept a wage lower than $\hat{w}\left(T^*\right)$ because, due to the imperfect monitoring mechanisms, they would not be able to credibly signal themselves as non-shirkers.

4.5 An example: Cobb-Douglas economy

In this section, we apply the framework introduced above by considering specific functional forms for the reservation utility function of workers and for the technology adopted by the firm. More precisely, we assume that the firm is characterized by the Cobb-Douglas production function

$$\Phi(N, T) = AT^{\alpha}N^{\beta}, \tag{4.17}$$

where $0 \leq T \leq T_{\max}$, $0 \leq N \leq \bar{N}$ and A is a scale parameter, that can be interpreted, for example, as an exogenous component of technical progress.

Workers' reservation utility function is of the type

$$\bar{U}(T) = T^{\gamma}. \tag{4.18}$$

On these parameters, we make the following assumptions:

Assumption 4.5 $\gamma > 1 > \alpha > 0.$

Assumption 4.6 $1 > \beta > 0.$

Assumption 4.7 $\beta\gamma > \alpha.$

These assumptions for the Cobb Douglas specification meet those made for the general case discussed in previous sections. Notice, however, that Assumption 4.5 is more restrictive than the corresponding Assumption 4.2 introduced in Section 4.2. Thus in the following pages, we will limit ourselves to illustrate a special case only of the general analysis performed above. In particular, we will consider an economy such that the technology of the firm is concave both in T and N, while the workers' reservation utility is convex in T. Both the concavity of the firm's production function and the convexity of the reservation utility in technology are not required in general, and we did not restrict our theory to these cases indeed. It is also immediate that in the Cobb-Douglas specification considered here technological progress is of the labor saving type in that $\frac{\partial^2 \Phi(N,T)}{\partial N \partial T} > 0$.

Notice, finally, that for all remaining variables and parameters we will stick to the notation introduced in the previous sections of the chapter.

4.5.1 The choice of technology and employment by the firm

We first solve the firm's profit maximization and characterize the choice of technology and labor demand by the firm using the same approach developed in Section 4.3.2.

The firm's profit maximization problem is

$$\max_{T,N} \quad \Pi(T,N) = AT^{\alpha}N^{\beta} - \left[T^{\gamma} + \frac{e}{c}\right]N, \tag{4.19}$$

where we already substituted for the individual rationality and no-shirking constraints (defined by Equation (4.7) in Section 4.2) that for this Cobb-Douglas economy takes the form

$$w = T^{\gamma} + \frac{e}{c}. \tag{4.20}$$

Given N, the technology adoption problem of the firm is

$$\max_{T} \quad AT^{\alpha}N^{\beta} - \left[T^{\gamma} + \frac{e}{c}\right]N, \tag{4.21}$$

which is represented in Figure 4.4.

The first order condition of Problem (4.21) is

$$\alpha AT^{\alpha-1}N^{\beta} - \gamma T^{\gamma-1}N = 0$$

and, for $T \neq 0$,

$$\alpha AN^{\beta} - \gamma T^{\gamma-\alpha}N = 0 \tag{4.22}$$

$$\Leftrightarrow t^*(N) := \left(\frac{\alpha A}{\gamma}N^{\beta-1}\right)^{\frac{1}{\gamma-\alpha}}. \tag{4.23}$$

Notice that, given Assumption 4.5, the second order condition for a local maximum is satisfied:

$$\underbrace{\alpha(\alpha-1)}_{<0}AT^{\alpha-2}N^{\beta} - \underbrace{\gamma(\gamma-1)}_{>0}T^{\gamma-2}N < 0. \tag{4.24}$$

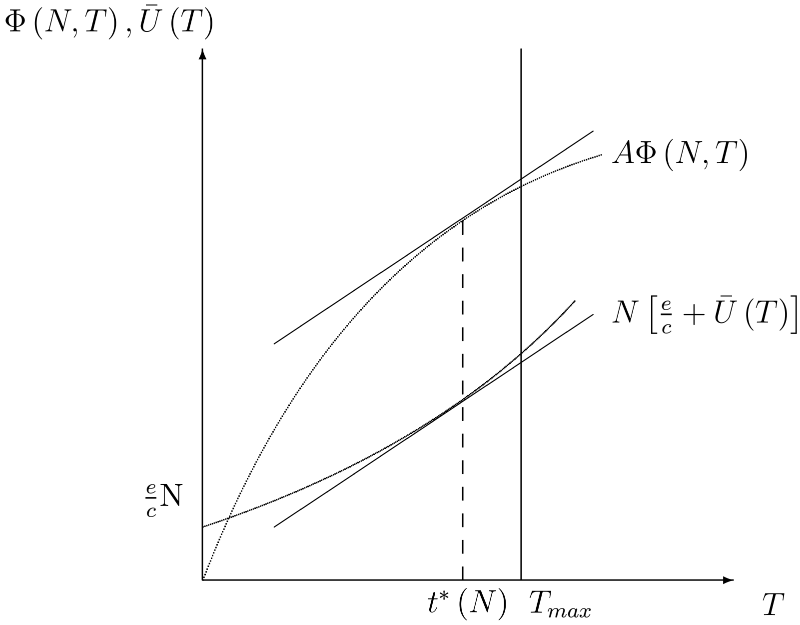

FIGURE 4.4. The technology of the firm and the reservation utility function

In order to derive labor demand, we substitute $t^*(N)$ for T into Problem (4.21) and we maximize with respect to N

$$\max_N \quad A\left(\frac{\alpha A}{\gamma}N^{\beta-1}\right)^{\frac{\alpha}{\gamma-\alpha}}N^{\beta}-\left[\left(\frac{\alpha A}{\gamma}N^{\beta-1}\right)^{\frac{\gamma}{\gamma-\alpha}}+\frac{e}{c}\right]N$$

i.e.

$$\max_N \quad A\left(\frac{\alpha A}{\gamma}\right)^{\frac{\alpha}{\gamma-\alpha}}N^{\frac{\beta\gamma-\alpha}{\gamma-\alpha}}-\left(\frac{\alpha A}{\gamma}\right)^{\frac{\gamma}{\gamma-\alpha}}N^{\frac{\beta\gamma-\alpha}{\gamma-\alpha}}-\frac{e}{c}N$$

$$\max_N \quad \left[A\left(\frac{\alpha A}{\gamma}\right)^{\frac{\alpha}{\gamma-\alpha}}-\left(\frac{\alpha A}{\gamma}\right)^{\frac{\gamma}{\gamma-\alpha}}\right]N^{\frac{\beta\gamma-\alpha}{\gamma-\alpha}}-\frac{e}{c}N, \tag{4.25}$$

illustrated graphically in Figure 4.5, where $k=\left[A\left(\frac{\alpha A}{\gamma}\right)^{\frac{\alpha}{\gamma-\alpha}}-\left(\frac{\alpha A}{\gamma}\right)^{\frac{\gamma}{\gamma-\alpha}}\right]$ and $\eta=\left(\frac{\beta\gamma-\alpha}{\gamma-\alpha}\right)$. It is a matter of algebra to show that k is greater than 0 for any A, as is proved in the following Lemma.

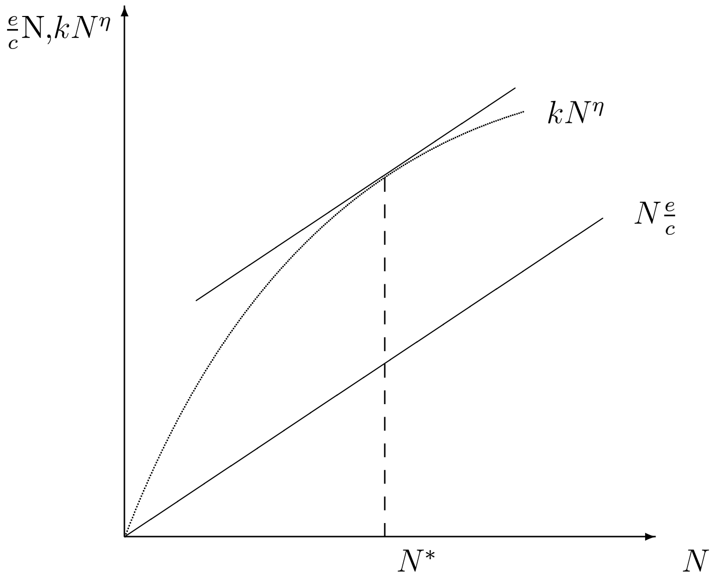

FIGURE 4.5. The firm's labor demand

Lemma 4.1

$$A\left(\frac{\alpha A}{\gamma}\right)^{\frac{\alpha}{\gamma-\alpha}} - \left(\frac{\alpha A}{\gamma}\right)^{\frac{\gamma}{\gamma-\alpha}} > 0.$$

Proof. By taking logarithms and after some algebra it is

$$\ln A \underbrace{\left(1 + \frac{\alpha}{\gamma-\alpha} - \frac{\gamma}{\gamma-\alpha}\right)}_{=0} >$$

$$\underbrace{\underbrace{\left(\frac{\alpha}{\gamma-\alpha} - \frac{\gamma}{\gamma-\alpha}\right)}_{\frac{\alpha-\gamma}{\gamma-\alpha}=-1} \underbrace{\ln \gamma}_{>0} + \underbrace{\left(\frac{\gamma}{\gamma-\alpha} - \frac{\alpha}{\gamma-\alpha}\right)}_{\frac{\gamma-\alpha}{\gamma-\alpha}=1} \underbrace{\ln \alpha}_{<0}}_{<0},$$

that is always satisfied. ■

The first order condition of Problem (4.25) is

$$k\eta N^{\eta-1} - \frac{e}{c} = 0$$

We already know that $k > 0$. Moreover, under Assumptions 4.5 - 4.7, it is $\eta > 0$. Therefore, we get:

$$N^* = \left(\frac{e}{c}\frac{1}{k\eta}\right)^{\frac{1}{\eta-1}} > 0.$$

Since $\beta < 1$ by Assumption 4.7, the exponent of N, i.e. $\eta = \frac{\beta\gamma-\alpha}{\gamma-\alpha}$, is smaller than 1. This ensures that the firm's problem in N has a maximum, as it is easily seen by studying the second order condition of Problem (4.25)

$$\underbrace{\left[A\left(\frac{\alpha A}{\gamma}\right)^{\frac{\alpha}{\gamma-\alpha}} - \left(\frac{\alpha A}{\gamma}\right)^{\frac{\gamma}{\gamma-\alpha}}\right]}_{>0}\underbrace{\frac{\beta\gamma-\alpha}{\gamma-\alpha}}_{>0}\underbrace{\frac{\gamma(\beta-1)}{\gamma-\alpha}}_{<0}\underbrace{N^{\frac{\gamma(\beta-1)}{\gamma-\alpha}-1}}_{>0} < 0.$$

Notice that, given A, α, β and γ, it is always possible to define $\bar{N}$ in such a way that an interior solution for N is obtained (i.e. $N^* < \bar{N}$), which implies the existence of involuntary unemployment in equilibrium.

We can, finally, determine the optimal technology adopted by the firm. Since by Equation (4.23) it is

$$t^*(N) = \left(\frac{\alpha A}{\gamma}N^{\beta-1}\right)^{\frac{1}{\gamma-\alpha}},$$

it is immediate that

$$T^* = t^*(N^*) = \left(\frac{\alpha A}{\gamma}\left(\frac{e}{c}\frac{1}{k\eta}\right)^{\frac{\beta-1}{\eta-1}}\right)^{\frac{1}{\gamma-\alpha}} = \left(\frac{\alpha A}{\gamma}\right)^{\frac{1}{\gamma-\alpha}}\left(\frac{e}{c}\frac{1}{k\eta}\right)^{\frac{1}{\gamma}}.$$

In order to check the existence and uniqueness of an interior solution (i.e. the result of inefficient technology adoption), we apply Proposition 4.1 introduced in Section 4.3.2. As for the existence part of the proposition, we only need to check whether the boundary Conditions (1) and (2) are fulfilled. By substituting Equations (4.17) and (4.18) into Conditions (1) and (2), we obtain respectively

$$\underbrace{A\alpha T^{\alpha-1}N^{\beta}\mid_{T=0}}_{\to+\infty} > \underbrace{\gamma T^{\gamma-1}N\mid_{T=0}}_{=0}, \tag{4.26}$$

and

$$A\alpha T_{\max}^{\alpha-1}N^{\beta} < \gamma T_{\max}^{\gamma-1}N \tag{4.27}$$

While inequality (4.26) is always satisfied, for Condition (4.27) to be met, it is sufficient to define a $T_{\max}$ such that $T_{\max} > T^{*} = t^{*}(N^{*})$, which is always possible as T^{*} is a finite number for any choice of the parameter values. This follows immediately from the fact that (4.27) can be rewritten as

$$T_{\max} > \left(\frac{\alpha A}{\gamma}N^{\beta-1}\right)^{\frac{1}{\gamma-\alpha}} = t^{*}(N),$$

where the equality is established by Equation (4.23). Finally, it is straightforward to notice that Assumption 4.4 holds for our Cobb-Douglas formulation, which proves uniqueness.

4.5.2 A note on the concavity of the firm's technology

By inspection of the Hessian matrix (4.28) for Problem (4.19), that is

$$\begin{bmatrix} \underbrace{\alpha(\alpha-1)AT^{\alpha-2}N^{\beta}-\gamma(\gamma-1)T^{\gamma-2}N}_{<0} & \underbrace{\alpha\beta AT^{\alpha-1}N^{\beta-1}-\gamma T^{\gamma-1}}_{?} \\ \underbrace{\alpha\beta AT^{\alpha-1}N^{\beta-1}-\gamma T^{\gamma-1}}_{?} & \underbrace{\beta(\beta-1)AT^{\alpha}N^{\beta-2}}_{<0} \end{bmatrix}, \tag{4.28}$$

it is easy to see that, in general, $\Pi(T, N)$ is not globally concave. By performing a contour analysis as the one presented in Figure 4.6 it is easy to check that, in general, the problem is not quasi-concave as well, since the resulting upper contour set is not convex.[16] Of course, it is always possible to introduce restrictions on parameters values in such a way that the problem becomes a concave one, but this turns out to be more restrictive than needed.As shown above, we can not base our claim that

[16] The non-convexity of the upper contour set is a feature of the problem for a wide range of parameter sets. Figure 4.6 - depicting contours $\Pi(T, N) = const.$ - has been drawn by setting $A = 4$, $\alpha = 0.5$, $\beta = 0.5$, $\gamma = 1.5$ and $\frac{e}{c} = 1$. The "biggest" contour corresponds to $const. = 1.8$ and

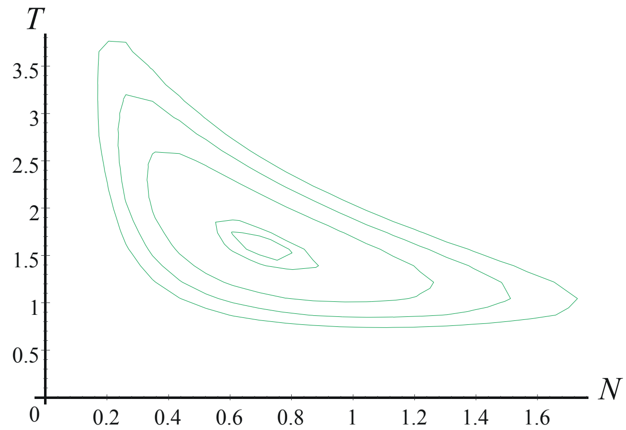

FIGURE 4.6. Contour sets for $\Pi(T, N)$

the values T^* and N^* are maximizers for Problem (4.19) on the concavity or quasi-concavity of $\Pi(T, N)$. However, the values obtained with our two steps procedure correspond to a global maximum of Problem (4.19). In fact, if $t^*(N)$ is a global maximizer for the problem in T given N and the second order condition of the problem in N is satisfied, the couple (T^*, N^*) identifies a global maximum for the original Problem (4.19).

By considering the left hand side of the first order condition (4.22), we note that, given a specific $N = \tilde{N}$, there is one and only one value of T (i.e. $t^*\left(\tilde{N}\right)$) such that the derivative $\frac{d\Pi\left(T,\tilde{N}\right)}{dT}$ is equal to 0. Given $\tilde{N}$, for all $T < t^*\left(\tilde{N}\right)$ such a derivative is positive, while for all $T > t^*\left(\tilde{N}\right)$ it is negative. Since this is true for all $\tilde{N} \in \left[0, \bar{N}\right]$, $t^*(N)$ is a global maximizer for the problem in T (given N) and not only a local one. Therefore, the maximizers of such a problem, for each N, are described by the locus $t^*(N)$.

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the others have been obtained by increasing monotonically the value *const*. The "smallest" contour represented corresponds to *const*. $= 2.15$.

4.5.3 The derivation of the loci $t^*(N)$ and $n^*(T)$

In this subsection we provide for an alternative characterization of the firm's choices — showing again the existence and uniqueness of an interior solution — that will prove useful in doing comparative statics exercises. In order to do so, we first derive the loci $t^*(N)$ and $n^*(T)$.

We know that

$$t^*(N) := \arg\max_T \quad AT^\alpha N^\beta - \left[T^\gamma + \frac{e}{c}\right] N, \tag{4.29}$$

and, from the first order condition of Problem (4.29), for $T \neq 0$, it is immediate to check that the expression for $t^*(N)$ is the one given by Equation (4.23).

By letting

$$n^*(T) := \arg\max_N \quad AT^\alpha N^\beta - \left[T^\gamma + \frac{e}{c}\right] N,$$

and taking the first order condition of such problem we get

$$n^*(T) = \left(\frac{T^{\gamma-\alpha} + \frac{e}{c}T^{-\alpha}}{\beta A}\right)^{\frac{1}{\beta-1}}. \tag{4.30}$$

A graphical representation of the loci $t^*(N)$ and $n^*(T)$ in the $T-N$ plane is provided in Figure 4.7, where the two loci have been plotted using the following parameters values[17]

$$\alpha = 0.25 \quad \beta = 0.5 \quad \gamma = 2 \quad \tfrac{e}{c} = 0.75 \quad A = 10. \tag{4.31}$$

We will use this parameters configuration as our *base parameters set* for all numerical experiments unless otherwise noted.

The qualitative behavior shown in Figure 4.7 is easily confirmed by observing that both $t^*(N)$ and $n^*(T)$ are continuos functions and that

$$\lim_{N\to 0} t^*(N) = +\infty, \quad \lim_{N\to+\infty} t^*(N) = 0$$

[17] Given these parameter values, the two loci have a unique intersection at $N^* = 17.68$ and $T^* = 0.5$.

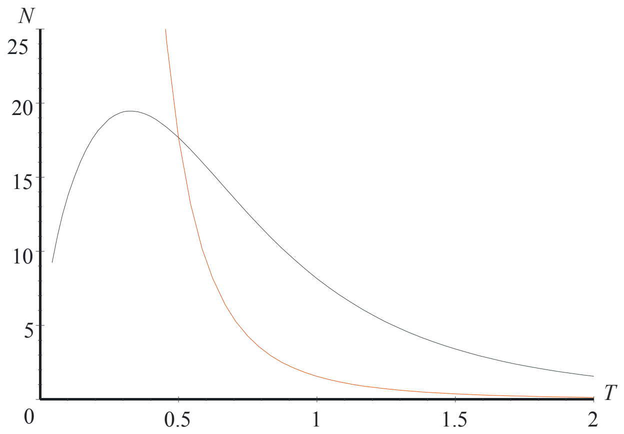

FIGURE 4.7. The loci $t^*(N)$ (red line) and $n^*(T)$ (black line)

and

$$\lim_{T\to 0} n^*(T) = 0, \lim_{T\to +\infty} n^*(T) = 0.$$

It is easy to show that the two loci $t^*(N)$ and $n^*(T)$ have a unique intersection. The corresponding equilibrium values for our Cobb-Douglas economy are

$$T^* = \left(\frac{\alpha\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{1}{\gamma}}, \tag{4.32}$$

$$N^* = \left[\frac{A\alpha^{\frac{\alpha}{\gamma}}}{\gamma}\left(\frac{\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-1}\right]^{\frac{1}{1-\beta}}, \tag{4.33}$$

and

$$w^* = \frac{\alpha\frac{e}{c}}{\beta\gamma-\alpha} + \frac{e}{c} = \frac{\beta\gamma}{\beta\gamma-\alpha}\frac{e}{c}. \tag{4.34}$$

In order to show the uniqueness of the equilibrium, notice that Equations (4.23) and (4.30) can be written as

$$t^{*^{-1}}(T) := \left(\frac{\alpha A T^{*^{\alpha}}}{\gamma T^{*^{\gamma}}}\right)^{\frac{1}{1-\beta}}, \tag{4.35}$$

$$n^*(T) := \left(\frac{\beta A T^{\alpha}}{T^{\gamma}+\frac{e}{c}}\right)^{\frac{1}{1-\beta}}. \tag{4.36}$$

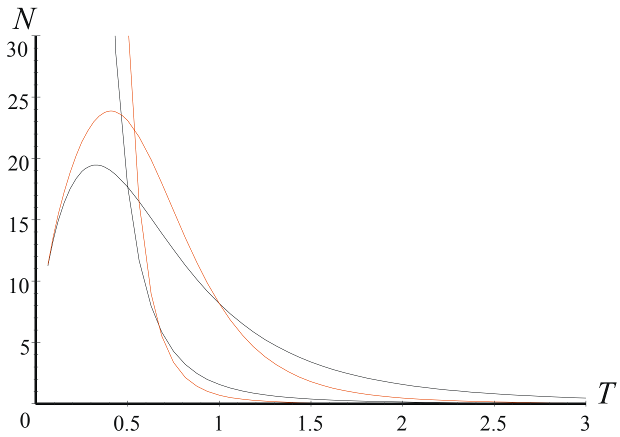

FIGURE 4.8. The loci $t^*(N)$ and $n^*(T)$ for $\gamma = 2$ (black lines) and $\gamma = 3$ (red lines)

By defining $\varsigma(T) := t^{*^{-1}}(T) - n^*(T)$, one finds that $\varsigma(T)$ has a unique zero at $T = T^*$, which proves uniqueness.[18]

4.5.4 Comparative statics

By having established the existence and uniqueness of the interior solution in T, we now turn to comparative statics. The position in the plane of the unique intersection between the two loci $t^*(N)$ and $n^*(T)$ is obviously affected by parameters values, as it is exemplified qualitatively by Figure 4.8, where — for the benchmark parameters set used in Figure 4.7 — we plot the loci $t^*(N)$ and $n^*(T)$ for different values of parameter γ.[19]

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[18] From Equations (4.35) and (4.36), one can see that it is $\varsigma(T) = 0$ if and only if

$$T^\gamma(\beta\gamma - \alpha) = \alpha\frac{e}{c}. \tag{4.37}$$

Since $\beta\gamma > \alpha$ by Assumption 4.7, it is

$$T^* = \left(\frac{\alpha\frac{e}{c}}{\beta\gamma - \alpha}\right)^{\frac{1}{\gamma}},$$

as stated in (4.32). By substituting (4.32) into Equation (4.36) we get the N^* defined in (4.33). Finally, by substituting (4.32) into the no-shirking constraint (4.20), the value w^* in (4.34) obtains.

[19] The equilibrium levels of employment and technology for the loci illustrated in Figure 4.8 are, respectively, $(N^*, T^*) = (17.68, 0.5)$ when $\gamma = 2$, and $(N^*, T^*) = (22.5, 0.53)$ when $\gamma = 3$.

In the following paragraphs, we study how the optimal values T^*, N^* and w^* are affected by changes in the relevant parameters, mainly focusing on the distortionary impact of the disutility of effort and of the probability to be caught shirking (reflecting the firm's monitoring technology), $(\frac{e}{c})$, and of the elasticity of the reservation utility function (γ).

The impact of changes in the disutility of effort/monitoring technology e/c on T^*, N^* and w^*

We discuss the impact of changes in $\frac{e}{c}$ by focusing, without loss of generality, on changes in the disutility of effort e.[20] The impact of the disutility of effort e on the choice of technology by the firm is determined by differentiating Equation (4.32) with respect to e, obtaining

$$\frac{\partial T^*}{\partial e} = \frac{1}{\gamma} \frac{\alpha}{c\,(\beta\gamma - \alpha)} \left(\frac{\alpha \frac{e}{c}}{\beta\gamma - \alpha} \right)^{\frac{1}{\gamma} - 1} \tag{4.38}$$

that, under Assumptions 4.5 - 4.7, is positive. This implies that the firm adopts better technologies the higher the disutility of effort. Moreover, from the non shirking constraint (4.20), it follows immediately that the wage is increasing in the disutility of effort, as confirmed by Condition (4.39):

$$\frac{\partial w^*}{\partial e} = \frac{\beta\gamma}{c} \frac{1}{(\beta\gamma - \alpha)} > 0. \tag{4.39}$$

Finally, since labor demand is decreasing in wage and labor supply is of infinite elasticity, the impact of e on optimal employment is a negative one, as confirmed by Condition(4.40), obtained by differentiating (4.33):

$$\frac{\partial N^*}{\partial e} = \underbrace{\frac{1}{1-\beta} \left[\frac{A\alpha^{\frac{\alpha}{\gamma}}}{\gamma} \left(\frac{\frac{e}{c}}{\beta\gamma - \alpha} \right)^{\frac{\alpha}{\gamma} - 1} \right]^{\frac{1}{1-\beta} - 1}}_{>0} \underbrace{\frac{A\alpha^{\frac{\alpha}{\gamma}}}{\gamma}}_{>0}.$$

[20] It is important to recall that in our framework both the disutility of effort and the probability to be caught shirking are modeled as exogenous parameters. We already discussed, however, the implications of rendering endogenous the firm's monitoring effort and hence the detection probability c.

$$\cdot \underbrace{\left(\frac{\alpha}{\gamma}-1\right)}_{<0}\underbrace{\left(\frac{\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-2}\frac{1}{c\left(\beta\gamma-\alpha\right)}}_{>0}<0. \tag{4.40}$$

It is important to notice that these results are specific to the Cobb-Douglas formulation we adopted. In general, the sign of $\frac{\partial T^*}{\partial e}$ can either be positive or negative depending on the value of the elasticity of substitution between factors. In this sense, the Cobb-Douglas case is a special one since the elasticity of substitution is equal to 1 and, thus, when e increases labor becomes more expensive, labor demand diminishes and the firm substitutes N with T. However, it is immediate to notice that, if the elasticity of substitution is smaller than 1, the sign of $\frac{\partial T^*}{\partial e}$ becomes negative as well. This can be easily illustrated considering a fixed proportion Leontief production function for which the elasticity of substitution is zero. In this case, in fact, when e increases labor demand and T (given fixed proportions) must decrease, which implies $\frac{\partial T^*}{\partial e}<0$.[21]

[21] The impact of changes in the monitoring technology, c, is immediately derived by an analogous argument. An increase of c affects positively the equilibrium demand of labor and negatively the wage (by lowering the wage required to meet the incentive compatibility constraint). Formally:

$$\frac{\partial N^*}{\partial c}=\underbrace{\frac{1}{1-\beta}\left[\frac{A\alpha^{\frac{\alpha}{\gamma}}}{\gamma}\left(\frac{\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-1}\right]^{\frac{1}{1-\beta}-1}\frac{A\alpha^{\frac{\alpha}{\gamma}}}{\gamma}}_{>0}\underbrace{\left(\frac{\alpha}{\gamma}-1\right)}_{<0}\underbrace{\left(\frac{\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-2}}_{>0}\underbrace{\left(-\frac{e}{c^2\left(\beta\gamma-\alpha\right)}\right)}_{<0}>0; \tag{4.41}$$

$$\frac{\partial w^*}{\partial c}=-\frac{\beta\gamma e}{c^2\left(\beta\gamma-\alpha\right)}<0. \tag{4.42}$$

Finally, since technology is labor saving and $\frac{\partial N^*}{\partial c}>0$, it must be $\frac{\partial T^*}{\partial c}<0$, as confirmed by Condition(4.43)

$$\frac{\partial T^*}{\partial c}=\frac{1}{\gamma}\left(\frac{\alpha\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{1}{\gamma}-1}\underbrace{\left(-\frac{\alpha e}{c^2\left(\beta\gamma-\alpha\right)}\right)}_{<0}<0. \tag{4.43}$$

The impact of changes of γ on T^*, N^* and w^*

The impact of changes in the elasticity, γ, of the reservation utility function on the equilibrium values depends on the sign of the derivative

$$\begin{aligned}\frac{\partial T^*}{\partial \gamma} &= \frac{1}{\gamma}\left(\frac{\alpha\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{1}{\gamma}-1}\left(-\frac{\alpha\beta\frac{e}{c}}{(\beta\gamma-\alpha)^2}\right)+ \\ &\left(\frac{\alpha\frac{e}{c}}{\beta\gamma-\alpha}\right)\ln\left(\frac{\alpha\frac{e}{c}}{(\beta\gamma-\alpha)}\right)\left(-\frac{1}{\gamma^2}\right),\end{aligned}$$

that, after some algebra, can be rewritten as

$$\frac{\partial T^*}{\partial \gamma} = -\frac{1}{\gamma}\left(\frac{\alpha\frac{e}{c}}{\beta\gamma-\alpha}\right)\left[\underbrace{\left(\frac{\alpha\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{1}{\gamma}-1}\left(\frac{\beta}{(\beta\gamma-\alpha)}\right)}_{>0}+\frac{1}{\gamma}\underbrace{\ln\left(\frac{\alpha\frac{e}{c}}{(\beta\gamma-\alpha)}\right)}_{\zeta(\gamma)\overset{?}{\gtreqless}0}\right]. \tag{4.44}$$

The sign of (4.44) is undecided, given that the expression $\zeta(\gamma)$ can be either greater or smaller than 0. It is immediate to notice that a sufficient condition for Derivative (4.44) to be negative is[22]

$$\gamma \leq \frac{\alpha\left(\frac{e}{c}+1\right)}{\beta}, \tag{4.45}$$

that occurs when $T^* \geq 1$, consistently with the view that for a sufficiently high "technological grade" the elasticity of the reservation utility function has a negative effect on technology adoption due to the relevance of spillover effects (externalities). Figure 4.9 — obtained for our base parameters set (4.31) — illustrates the switch in the sign of the derivative. Moreover, Condition (4.45) makes apparent the link between γ and the disutility of effort $\frac{e}{c}$, as well as the production function coefficients α and β. The value of γ at which the switch in the sign of the derivative occurs is clearly a numerical issue depending on the specific parameters set

[22] Assumption 4.7 requires that $\gamma > \frac{\alpha}{\beta}$. Moreover, condition $\gamma \leq \frac{\alpha\left(\frac{e}{c}+1\right)}{\beta}$ guarantees that $\ln\left(\frac{\alpha\frac{e}{c}}{(\beta\gamma-\alpha)}\right) \geq 0$.

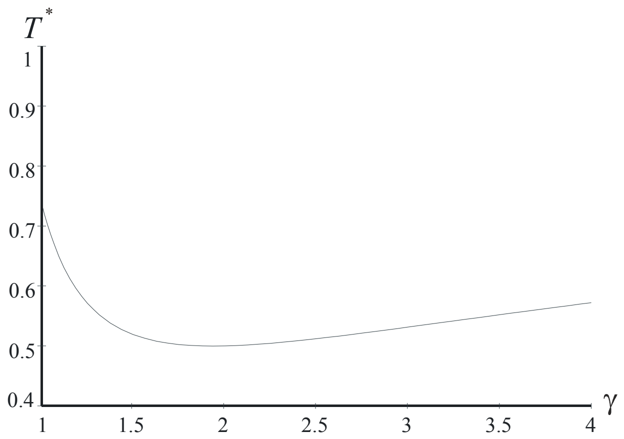

FIGURE 4.9. Non-monotonic dependence of T^* on γ

considered. It is worth noticing that, as illustrated by Condition (4.45), increasing the value of the disutility of effort (or relaxing the firm's monitoring technology, i.e. reducing c) increases the value of γ at which the sufficient condition for γ begins to hold.[23] This is shown in Figure 4.10 reporting simulations for different values of the disutility of effort (monitoring technology). The experiment is performed for the same parameter set as in Figure 4.9 and for various $\frac{e}{c}$ values: $\frac{e}{c} = 0.25$ (magenta line), $\frac{e}{c} = 0.5$ (blue line), $\frac{e}{c} = 0.75$ (black line), $\frac{e}{c} = 1$ (red line), and finally $\frac{e}{c} = 1.5$ (green line). This evidence suggests that the change in the sign of the derivative depends on the distortionary impact of the disutility of effort (or of the firm's monitoring) on the firm's choice of technology.

Turning to the impact of γ on w^*, it is immediate to observe that it is always negative, as confirmed by the fact that the sign of

$$\frac{\partial w^*}{\partial \gamma} = \frac{\beta \frac{e}{c} (\beta\gamma - \alpha) - \beta^2 \frac{e}{c} \gamma}{(\beta\gamma - \alpha)^2} = -\frac{\alpha\beta\frac{e}{c}}{(\beta\gamma - \alpha)^2} \tag{4.46}$$

[23] Further experimentations, not reported here, with different values of the parameters show that, given $\frac{e}{c}$ and α, the value of γ at which the derivative turns positive becomes smaller when increasing β. In the same way, given $\frac{e}{c}$ and β, the derivative becomes positive for a smaller value of γ when decreasing α.

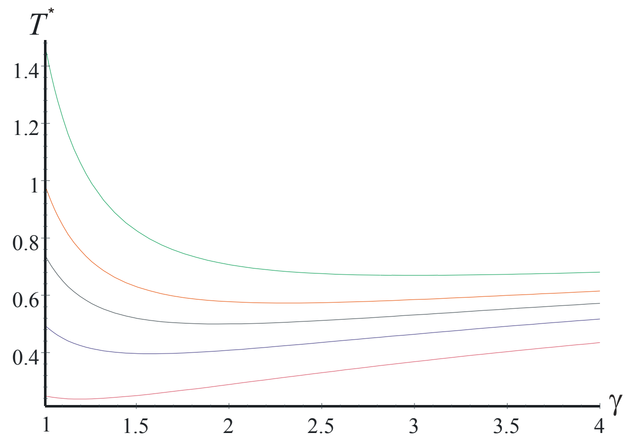

FIGURE 4.10. Joint effects of $\frac{e}{c}$ and γ on T^* ($\frac{e}{c}$ = 0.25, 0.5, 0.75, 1, and 1.5)

is negative. This is an intuitive finding, given the behavior of $\frac{\partial T^*}{\partial \gamma}$. When Condition(4.45) holds, it is $\frac{\partial T^*}{\partial \gamma} < 0$ and therefore the results follows directly from Equation (4.20). When Condition (4.45) does not hold, it is $T^* < 1$. Thus, again from Equation (4.20), it is immediate to conclude that an increase in γ reduces the wage.

Finally, as for the behavior of N^* with respect to γ, it is easy to show (see Appendix A.1) that the sign of $\frac{\partial N^*}{\partial \gamma}$ is undecided, as it depends on the specific parameters values for the disutility of effort - monitoring technology ($\frac{e}{c}$), and for the production function parameters α and β.[24]

The impact of changes in α and β on T^*, N^* and w^*

Changes in the parameters β and α reflect changes in the distributional ratio between technology and labor expenditures. It is thus interesting to investigate the impact of the quota spent in technology and labor by the firm (the production function coefficients α and β respectively) on the equilibrium values. From Equations (4.32) and (4.34) it is straightforward to establish the signs of the derivatives of w^* and T^* with respect to α,

[24]See Appendix A.1 for numerical experiments investigating the impact of γ on the equilibrium employment level.

i.e.

$$\frac{\partial w^*}{\partial \alpha} = \frac{\beta\gamma\frac{e}{c}}{(\beta\gamma-\alpha)^2} > 0, \tag{4.47}$$

$$\frac{\partial T^*}{\partial \alpha} = \underbrace{\frac{1}{\gamma}\left(\frac{\alpha\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{1}{\gamma}-1}}_{>0}\underbrace{\left(\frac{\frac{e}{c}(\beta\gamma-\alpha)+\alpha\frac{e}{c}}{(\beta\gamma-\alpha)^2}\right)}_{>0} > 0. \tag{4.48}$$

Similarly, by taking the derivatives with respect to β,we obtain

$$\frac{\partial w^*}{\partial \beta} = \frac{\gamma\frac{e}{c}(\beta\gamma-\alpha)-\beta\gamma^2\frac{e}{c}}{(\beta\gamma-\alpha)^2} = -\frac{\alpha\gamma\frac{e}{c}}{(\beta\gamma-\alpha)^2} < 0, \tag{4.49}$$

$$\frac{\partial T^*}{\partial \beta} = \underbrace{\frac{1}{\gamma}\left(\frac{\alpha\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{1}{\gamma}-1}}_{>0}\underbrace{\left(-\frac{\gamma\alpha\frac{e}{c}}{(\beta\gamma-\alpha)^2}\right)}_{<0} < 0. \tag{4.50}$$

While the impact of α and β on equilibrium wage and technology is as expected from economic intuition, the effect of the coefficients α and β on the equilibrium level of employment turns out to be less clear-cut, since the signs of $\frac{\partial N^*}{\partial \beta}$ and of $\frac{\partial N^*}{\partial \alpha}$ — depending on the specific parameters values — are undecided.[25] We consider $\frac{\partial N^*}{\partial \alpha}$ first. By differentiating Equation (4.33) with respect to α, making use of Assumptions 4.5 - 4.7 and after some algebra we get

$$\frac{\partial N^*}{\partial \alpha} = \underbrace{\frac{1}{1-\beta}\xi^{\frac{\beta}{1-\beta}}\frac{A}{\gamma}\left(\frac{e/c}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-1}\frac{\alpha^{\frac{\alpha}{\gamma}}}{\gamma}}_{>0}\left[\underbrace{\frac{\gamma(\beta-1)}{\beta\gamma-\alpha}}_{<0}+\underbrace{\ln\alpha\frac{e/c}{\beta\gamma-\alpha}}_{\gtreqless 0 \, ?}\right], \tag{4.51}$$

where

$$\xi = \frac{A\alpha^{\frac{\alpha}{\gamma}}}{\gamma}\left(\frac{e/c}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-1} > 0. \tag{4.52}$$

[25] It is worth noticing that the issue can not be solved by studying directly the effect of the distributional ratio $\frac{\alpha}{\beta}$ only. In fact, from Equation (4.33), one can easily conclude that N^* can not be immediately expressed as a function of $\frac{\alpha}{\beta}$.

Although there are no immediate conditions fully characterizing the sign of (4.51), it is easy to see that a sufficient condition for it to be negative is

$$0 < \alpha \leq \frac{\beta\gamma}{e/c+1} < 1. \tag{4.53}$$

From Equation (4.32) it is clear that Condition (4.53) holds when it is $T^* \leq 1$, suggesting that the fraction of firm's expenditures in technology has a negative impact on equilibrium employment when the "technology grade" is sufficiently low.[26] Figure 4.11-(a) shows the behavior of $N^*(\alpha)$ for our benchmark parameters set (4.31). It is straightforward to notice that, although $N^*(\alpha)$ is decreasing everywhere, sufficient Condition (4.53) is not fulfilled for all α.[27] Panels (b) — drawn for $e/c = 5$ — and (c) — for $e/c = 10$ — illustrate the possible non-monotonicity of $N^*(\alpha)$ when increasing, for example, the value of e/c.

As for the sign of $\frac{\partial N^*}{\partial \beta}$, by differentiating (4.33) with respect to β, and using (4.52) and Assumptions 4.5 - 4.7, after some algebra we get

$$\frac{\partial N^*}{\partial \beta} = \underbrace{\frac{1}{(1-\beta)^2}}_{>0} \underbrace{\xi^{\frac{1}{1-\beta}}}_{>0} \underbrace{\ln \xi}_{\stackrel{?}{\gtreqless} 0} + \underbrace{\xi^{\frac{\beta}{1-\beta}}}_{>0} \underbrace{\frac{\frac{e}{c}\frac{\gamma-\alpha}{\gamma} A\alpha^{\frac{\alpha}{\gamma}}}{(1-\beta)\left(\frac{e/c}{\beta\gamma-\alpha}\right)^{2-\frac{\alpha}{\gamma}} (\beta\gamma-\alpha)^2}}_{>0}, \tag{4.54}$$

from which it is apparent that the sign of $\frac{\partial N^*}{\partial \beta}$ is affected by the value of ξ, that in turn depends on the specific parameters values. By inspection of (4.54) it is, in fact, immediate to notice that a sufficient condition for $\frac{\partial N^*}{\partial \beta} > 0$ is to require $\xi \geq 1$, i.e.

$$\frac{1}{\gamma}\left(\frac{e}{c}\left(\frac{A\alpha^{\frac{\alpha}{\gamma}}}{\gamma}\right)^{\frac{\gamma}{\gamma-\alpha}} + \alpha\right) \leq \beta < 1, \tag{4.55}$$

[26] Notice that Condition (4.53) requires exactly the opposite than Condition (4.45) providing sufficient conditions for $\frac{\partial T^*}{\partial \gamma}$ to be negative.

[27] Condition (4.53) obviously holds for all admissible α if and only if $\beta\gamma \geq \frac{e}{c}+1$, a condition that is not satisfied by our parameters set for which, instead, sufficient Condition (4.53) holds for $\alpha \leq 0.57$ only.

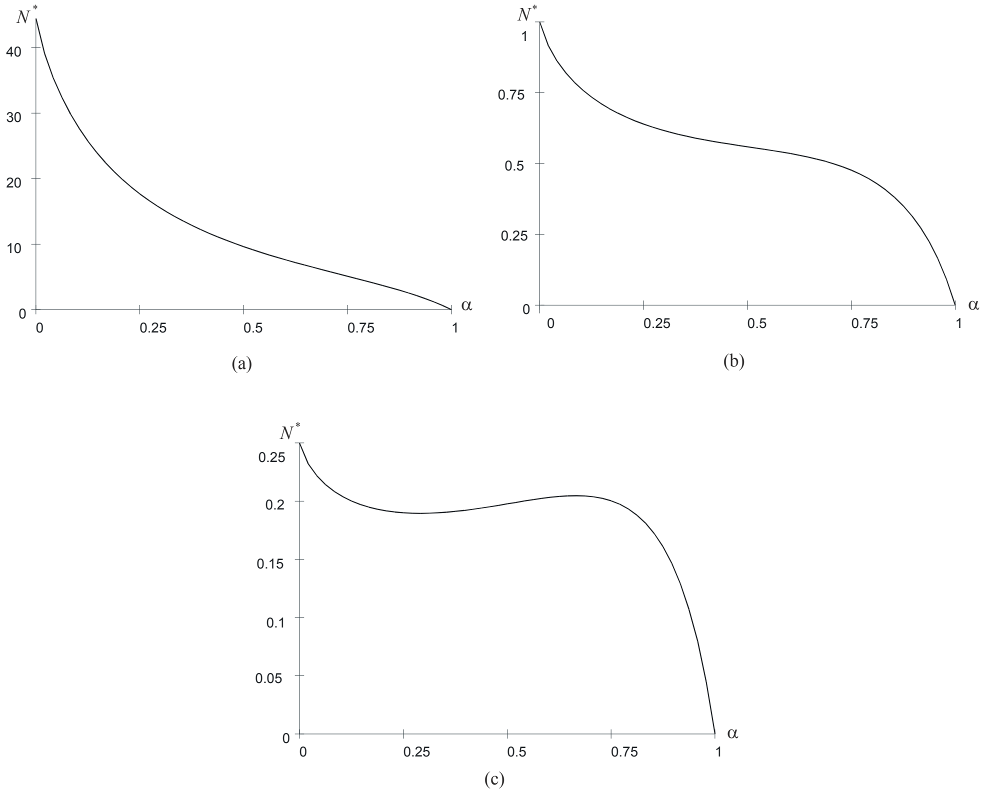

FIGURE 4.11. The shape of of $N^*(\alpha)$ for different values of e/c

that does not have a clear economic interpretation. The positively slope curve in Figure 4.12-(a) is drawn for the base parameters set (4.31) for which Condition (4.55) is satisfied for (almost) all admissible β, while the curve in panel (b) is obtained by changing the value of A to $A = 1$ in order to show the possible non-monotonicity of $N^*(\beta)$.[28]

Appendix A.2 contains further numerical experiments investigating the cross effects of γ and $\frac{e}{c}$ on $N^*(\alpha)$ and $N^*(\beta)$.

[28] For $A = 1$ there are no admissible values of β that fulfill Condition (4.55). For our benchmark parameters set, Condition (4.55) is satisfied for $0.197 \leq \beta < 1$. Given the values of α and γ, it must be $\beta > 0.125$ for Assumption 4.7 to hold. However, we do not report experiments with parameters configurations such that (4.55) is met by all admissible values of β as $\partial N^*(\beta)/\partial\beta$ tends to infinity for very small values of β.

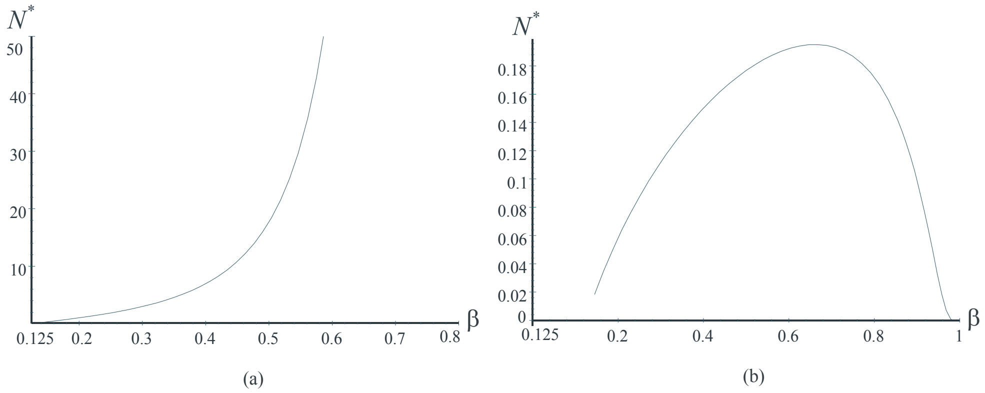

FIGURE 4.12. The shape of $N^*(\beta)$ for different values of A

4.6 Summary and Extensions

In this chapter we investigated, in a partial equilibrium setting, the technology adoption problem faced by a firm that is price maker on the labor market and price taker on the goods market. The main feature of our economy is the specific relationship between the reservation utility of workers and the technology adopted by the firm. The adoption of a superior technology improves the workers' outside options, inducing an increase in the wage the firm must pay in order to induce them to participate in the employment relationship. It is proved that such increase in the wage can be enough to dampen the adoption of better technologies. The direct implication of this is an inefficiency result in the technology adoption problem. However, as stressed in Chapter 3, the channel through which this result is obtained differs substantially from those typically emphasized in the literature, that focuses mainly on the direct role of adoption and adjustment costs to explain why firms do often choose inferior technologies.

The chapter focused on a simple framework to highlight the role of spillover effects, and most of the assumptions made, whether implicitly or explicitly, are mainly motivated by this objective. In principle, the same issues can be investigated in a broader and more general modelling environment. In the following, we briefly survey some of the limits and outline specific extensions to the framework developed in the previous sections.

Probability to be fired. The simplifying assumptions on the probability to be fired and to be re-hired can be generalized. By assuming the probability to be re-hired being equal to zero, we rule out some features that can be included in the model. In case $\bar{N}$ is not big enough, it may be possible that the number of workers fired because of shirking is bigger than the number of those never employed by the firm. If this happens, on the one hand, the firm may be forced to hire workers it fired in the past and this, of course, reduces the punishment associated with being fired. Moreover, as already observed, the assumption of an ever-lasting unemployment phase becomes contradictory should the economy be close to a full employment equilibrium. On the other hand, in the case of labor-saving technical progress the likelihood of being re-hired once fired is reduced, thus reducing the wages the firm must pay in order not to induce shirking behaviors. This effect would be reinforced by taking into account the heterogeneity of workers while evaluating the probability of being re-hired. In fact, once fired, a shirker suffers a loss of reputation, which makes more difficult for him (her) to be hired again.

Risk neutrality of workers and absence of a capital market. In describing the economy, we have assumed a quasi-linear utility function and, hence risk neutrality of workers. In a more general framework in which self-employed agents can transform into entrepreneurs — or take advantage of their knowledge if employed by other firms (which amounts to a more advanced modelling of workers outside options) —, allowing for risk aversion would reduce the probability that a worker is willing to convert into an entrepreneur (i.e. enter the "subsistence sector of the economy in the terminology of the previous sections) in order to take advantage of the knowledge she acquires while working for the firm, provided uncertainty is higher when being self-employed than when working for the firm. This of course amounts to a decrease in the value of the worker's outside option, that in turn reduces the importance of the spillover effects associated to the adoption of a better technology and, ultimately, the costs of innovation for the firm.

The presence of an (imperfect) capital market is likely to have a similar impact, whenever one explicitly allows for positive adoption (development) costs of technology. Maintaining the assumption of risk neutrality, a worker that wants to become an entrepreneur may not succeed in doing so whenever she is unable to obtain the financial resources she needs. Therefore, the possible relevance of binding financial constraints may render impossible for workers to exploit the better outside options originating from technology-induced spillovers. This, in turn, reduces the importance of the latter in the firm's decision to adopt a superior technology.

Number of firms. The assumption of a market sector characterized by the presence of one firm only does not add to the realism of the analysis, being as it is — in many cases — at odds with the empirical evidence. We conjecture, nonetheless, that it may be a less restrictive assumption than it appears at first. The central point in this chapter's modelling strategy is, in fact, the presence of market power on the labor market and not the degree of competition in the final goods market. On the one hand, allowing for many firms competing on the labor market certainly complicates the analysis of the interaction between firms and workers, possibly determining a strategic use of the adoption timing by different firms.[29] On the other hand, however, provided that the degree of com-

[29] The point has been discussed in Chapter 2. There are many papers investigating both theoretically and empirically the interaction among firms. For instance, Spence (1984) stresses that the presence of spillovers reduces the production costs of rival firms generating free riding problems. At the empirical level, Bernstein (1988) studies the impact of spillovers both at the inter-industry and

plementarity among different industries is not too low (rendering firm-specific the knowledge accumulated by workers, and hence reducing the potential relevance of spillovers), the presence of many firms should increase the dimension of the space of outside options available to workers, eventually increasing the size of the technology-induced spillover effects and, thus, the cost of technology adoption for the firm.

at the intra-industry level and Bernstein and Nadiri (1991) investigate private and social returns from R&D investments.

5

Technology Adoption with Production Externalities: A General Equilibrium Framework

5.1 Introduction

In this chapter, we further investigate the impact of the links between market power and technology in impeding or slowing down the adoption of superior technologies. As in Chapter 4, our main claim is that the presence of perfectly competitive goods markets, and monopolistic factors markets can slow down the adoption of better technologies and thus technical progress. The presence of an imperfectly competitive labor market combined with that of production externalities — a new ingredient of this chapter to model consistently the technology-induced spillovers — can impede economic progress and drive the adoption of inefficient technologies, even in the absence of any form of coordination among agents.

The main contribution of this chapter with respect to our previous analysis is that we now turn our attention to a general equilibrium economy, extending the partial equilibrium framework developed in Chapter 4. The structural characteristics of the economy developed here are the same considered there, except that we model explicitly the relationship between the technology adopted by the firm and the workers' outside options (i.e. the spillover effects). One of the main disadvantages of the partial equilibrium analysis in Chapter 4 is, in fact, that the dependence of the workers' reservation utility on technology — and thus the nature of the spillover effects on which our arguments are based — remains unexplained, being exogenously stated by assumption. As it will become clear after the model is presented, the general equilibrium framework studied in this chapter allows to render endogenous such relationship by means of production externalities going from the market sector to the self-employment sector of the economy.

Furthermore, in a general equilibrium framework, all feedback effects arising from the link between technology and outside options — and influencing the consumers' decisions on labor supply, the wages and the firm's choice of technology — are endogenous and fully taken into account. At the same time, the economy is closed, in the sense that all monetary and real flows are accounted for, and the income determination process is both endogenous and complete, meaning that all income generated is used.

The economy is made up of a consumption sector, characterized by a finite number of identical consumers, and of a production sector — producing a consumption good — composed of a price-taker firm (whose shares are equally held by all agents in the economy), which we label as the market sector, and a number of self-employed entrepreneurs (workers). Excluding self-employment, the firm is a monopsonist in the labor market and, besides technology, uses labor as the only input of its production function. As for the self-employed, their labor productivity is affected by a production externality depending on the technology adopted by the firm. Finally, as in Chapter 4, and for the same reasons, we assume that it is impossible for other firms to enter the industry. Consumers can therefore be in one of three situations: employed by the firm, self–employed or unemployed.

We focus on the choice of technology by the market sector firm under two different scenarios. First, we assume that both the firm itself and the self-employed entrepreneurs take the technology-induced externality as an exogenous parameter (a situation that we label as Cournot - Nash case). Under this assumption, that neglects the role of the externality and therefore mimic a perfectly competitive environment, we show that the presence of the externality does not imply neither labor nor technology misallocation.

Second, we replace the Cournot setting with one in which the competition among producers is *à la* von Stackelberg. For the sake of illustration, one can see the competition between the market sector and the self-employment sector as a two stage game of perfect information. In the first stage, the market firm chooses the technology to be adopted and determines its labor demand and wage. In the second one, workers decide on their labor time when self-employed given the technology adopted by the firm. Since the game is one of perfect information, it can be logically solved by backward induction, assuming that the firm takes into account the impact of its technology choice on the self-employed entrepreneurs' decision problem (i.e. the endogeneity of the participation constraint in technology). In this case, the adoption of a better technology generates a positive externality that workers can exploit by becoming (self-employed) entrepreneurs. This, in turn, renders the participation constraint the firm must satisfy in order to induce a worker to remain employed — and the corresponding wage offer — endogenous in the technology chosen. Finally, as in the partial equilibrium framework investigated in Chapter 4, the increase in wage associated to the choice of a better technology can become big enough to induce the market firm not to adopt it, giving rise to technology misallocation with respect to the Cournot case.

The chapter is organized as follows. Section 5.2 studies the economy discussing the consumption and the production sector. Section 5.3 focuses on the Cournot competition among producers, showing the existence and uniqueness of the Cournot - Nash equilibrium, and that there is not technology misallocation. Section 5.4 focuses on von Stackelberg competition, proving that technology misallocation becomes possible. Different technology adoption regimes are identified, a definition of von Stackelberg equilibrium is provided, as well as a discussion of the condition for its existence and uniqueness. Section 5.5 provides an application of the chapter results to a general equilibrium version of the Cobb-Douglas economy introduced in Chapter 4. The last section concludes and outlines possible extensions.

5.2 The economy

The economy is again composed of $\bar{N}$ identical consumers and an industrial sector that produces a consumption good.[1] Besides technology, labor is the only input of production and the price of consumption is normalized to unity without loss of generality. The choice of the numeraire good has no real effects within the general equilibrium framework here, although, in general, in economies with imperfect competition it affects the equilibrium allocation (see Böhm, 1994, and Myles, 1995, Ch. 11).

The industry is composed of a firm, and a large number of self-employed entrepreneurs/workers (denoted with f). We first describe consumers' choices and then turn to producers' behavior.

5.2.1 The consumption sector

Each consumer can supply one unit of labor (i.e. a fixed labor time given exogenously) to the firm or work as a self-employed. She derives income from labor and obtains an equal share of the profits generated by the firm. All consumers in the economy are characterized by a utility function of

[1] Whenever not misleading, we stick to the notation introduced in Chapter 4.

the type

$$V(x,h) = x - \varphi(h), \tag{5.1}$$

where x is consumption, $\varphi(h)$ is the (consumption-equivalent) disutility of labor and h denotes labor time, with

Assumption 5.1 *$\varphi \in C^2$, $\varphi(0) = \varphi'(0) = 0$, $\varphi'(h) > 0$, $\varphi''(h) > 0, h > 0$.*

Quasi-linearity in x implies that there are no income effects in the demand for the consumption good.

We assume that the firm has an imperfect monitoring technology and hence we allow for the possibility of shirking by workers employed by the firm. Without loss of generality, we take the disutility of labor for a shirker to be equal to 0, which is standard in the efficiency wage literature. Since labor time is exogenous and supplied inelastically when working for the firm, the disutility of labor can take only one of two values. If a worker does not exert effort it is $\varphi(h) = 0$; if she exerts the desired level of effort it is $\varphi(h) = e > 0$. For a self-employed worker, labor disutility is $\varphi(h_f)$, which depends on labor time. We assume that a self-employed does not have an incentive to shirk (or, which has the same consequences, that there is perfect monitoring in the self-employment sector). If an agent is unemployed (u) she does not exert any effort.

Hence, each consumer makes a choice among four options: work for the firm and shirk (s), work for the firm and not shirk (ns), to be self-employed (f) and, finally, to stay unemployed (u). The utility levels associated to the four options are derived from the corresponding expected utility maximization problems.

Consider first the case of workers employed by the firm. Two different utility maximization problems have to be studied for shirker and non-shirker workers. Since labor time is given exogenously, the disutility of effort can take one of two values: $\varphi(h) = e$ when the worker exerts the desired level of effort and 0 when she shirks. Therefore, a worker must choose her optimal consumption level x and her level of effort (where the latter is a binary choice).The non-shirkers are those who exert the required level of effort (e). Recalling that the consumption good price is set equal to 1, it is

$$\begin{cases} \max_{x} V^{ns} = x - e \\ \text{s.t.} \quad x \leq w + \pi \end{cases}, \tag{5.2}$$

where w is the wage paid by the firm and π is the share of the firm profits going to each consumer. As for the latter, along the same lines of Chapter 4, we assume that

Assumption 5.2 $\pi = \Pi/\bar{N}$, *where* Π *are total profits.*

We think of the firm as a corporation so that the $\bar{N}$ identical consumers, all making the same portfolio choice, hold a fraction $1/\bar{N}$ of shares and hence receive dividends π. This assumption on the ownership structure of the firm is obviously quite extreme and there are many possible alternative and more realistic profit distribution schemes that could be considered. One can assume for instance that profits are accruing to a subset of the population only. As far as a shareholder is not a worker of the firm (or better can not benefit directly or indirectly of the adoption of a superior technology by the firm), any profit distribution mechanism would not interfere with her decisions on labor allocation. However, as soon as an agent is at the same time a shareholder and a worker, she should take into account the impact of technology choices both on the share of profits (dividends) she is entitled to, and on the labor income she receives from the firm. A scheme of this type, by introducing additional feedback effects to be taken into account in a general equilibrium framework,would further complicate the analysis without however being central to our argument.

From Problem (5.2), it is immediate that $x = w + \pi$ and the corresponding expected utility level is specified by Equation (5.3).

$$V^{ns} = w + \pi - e. \tag{5.3}$$

Similarly, for the shirkers (exerting no effort) it is

$$\begin{cases} \max\limits_{x^0, x^1} V^s = (1-c)\, x^1 + c x^0 \\ \text{s.t.} \quad x^1 \leq w + \pi \\ \qquad\;\; x^0 \leq \pi \end{cases}, \tag{5.4}$$

where x^1 denotes consumption when a shirker is not caught shirking and x^0 when she is caught shirking and is fired, and $c \in (0,1)$ is the probability to be caught shirking when employed by the firm. As in Chapter 4, we take the firm's monitoring technology as given exogenously, thus ruling out the possible links among the firm's technology choice and monitoring. From Problem (5.4) it follows immediately that $x^1 = w + \pi$ and $x^0 = \pi$, and thus the corresponding expected utility level is

$$V^s = (1-c)(w + \pi) + c\pi. \tag{5.5}$$

Turning now to the self-employed consumers, they maximize expected utility both over labor time h_f and consumption x_f. By taking labor time as given (we will solve explicitly for it in Problem (5.8) in the next section), their expected utility level is derived in the same way as above, obtaining

$$V_f = w_f + \pi - \varphi(h_f), \tag{5.6}$$

where w_f is gross-income of a self-employed worker. Finally, for the unemployed agents it is

$$V_u = \pi. \tag{5.7}$$

Notice that π is the only source of income for the unemployed. In particular, there are no unemployment benefits.

Each consumer chooses the option that maximizes her welfare, among feasible options. Whenever any two options give the same utility level, we assume that preferences are such that:

Assumption 5.3 *If* $V^{ns} = V^{s}$ *then* $ns \succ s$*. If* $V^{s} = V_f$ *then* $s \succ f$*. If* $V_f = V_u$ *then* $f \succ u$*.*

5.2.2 The production sector

Self-employed entrepreneurs

Self-employed entrepreneurs are characterized by a production function incorporating a production externality via the technology adopted by the market sector firm of the form gh_f, where g captures the production externality. For any given g, hence, there are constant returns in labor. The self-employed agents are unable to influence the technology adopted by the firm and therefore take the production externality as a given parameter, i.e. $g = G$, when solving their decision problem.

Given that, as we will show below, the firm's problem includes the participation constraint of workers (which takes into account the outside option represented by self employment), by Assumption 5.3 only workers not employed by the firm are potentially interested in being self-employed, which acts therefore as an outside option.

Self-employed workers solve the following problem

$$h_f(G) := \arg\max_{h_f} \quad Gh_f - \varphi(h_f), \tag{5.8}$$

which gives $G = \varphi'(h_f)$ as a first order condition. By Assumption 5.1, the optimal h is unique and non negative. Denoting the (labor) income of a self-employed entrepreneur with $W_f(G)$, it is[2]

$$W_f(G) := Gh_f(G). \tag{5.9}$$

Hence the indirect utility of a self–employed is

$$V_f(G) := W_f(G) - \varphi(h_f(G)) + \pi. \tag{5.10}$$

[2] It is immediate to note that the marginal return on labor is equal to the (exogenous) marginal productivity G.

Notice, finally, that instead of self employment, we could have modelled sector f as a perfectly competitive industry that uses only labor as an input. This alternative specification is equivalent to the chosen one provided that: a) there are constant returns to scale, i.e. the production function of the individual firm j is of the type GN_f^j, where N_f^j is its labor input; b) there is perfect monitoring in sector f.

The market sector firm

Next, we consider the market sector, i.e. the externality producer, problem. The firm has a production function $\Phi(N,T)$ — where N denotes the labor input and T the technology adopted — satisfying the following assumptions:

Assumption 5.4 $\Phi \in C^2$, $\forall\, (N,T) \gg 0 : \dfrac{\partial \Phi}{\partial T} > 0,\ \dfrac{\partial \Phi}{\partial N} > 0,\ \dfrac{\partial^2 \Phi}{\partial N^2} < 0,$ $\lim\limits_{N \to 0} \dfrac{\partial \Phi}{\partial N} = +\infty.$

While we assume decreasing returns in labor input, we do not impose any restriction on technology returns. Moreover, we assume that technology adoption is a costless and continuous choice available within an exogenously given range.

Assumption 5.5 $T \in [0, T_{\max}]$. *There are no adoption costs and no price must be paid to install any available technology.*

As already stressed when discussing the partial equilibrium model in Chapter 4, the assumption that a superior technology can be chosen without suffering adoption (or adjustment) costs, although clearly simplistic, does not seem problematic in our framework, even though it requires some cautions. On the one hand, the adoption costs often required in the literature to explain why superior technologies are not installed — besides being in many circumstances of too large a magnitude with respect to what reported by the available empirical evidence (see the discussion in Chapter 2) — reinforce the role of the externality (i.e. spillover) discussed here in slowing down the adoption of a higher technology grade. On the other hand, the idea that once introduced by a firm a technology becomes freely available makes it easier for agents to put it at work elsewhere as well.[3] In our setting, the self-employment sector is just a compact way to model the set of outside options available to workers. The ability to exploit the externalities generated by the decision of the firm to adopt a better technology increases workers' productivity in the self-employment sector, and thus their reservation income and their bargaining power. Introducing an adoption cost (and/or a price) for the technology would therefore make it more difficult for workers to directly take advantage of the technology (for instance by adopting it as self-employed entrepreneurs). This would not imply, however, that a worker can not benefit elsewhere from the "skills" (i.e. technical knowledge) she acquired operating the technology (benefits that are here modeled in the form of a production externality), provided such skills are not entirely specific.

Note, finally, that $T_{\max}$ represents the best available technology given the "state of the art" of current scientific know-how, which is publicly available at no cost. Matters are different when the process of innovation is explicitly taken into account. In this case, the technology frontier ($T_{\max}$) becomes endogenous in the firm's investments in R&D (or managerial reorganization, and so on). Thus costs associated with moving the frontier can be substantial and likely to become (as emphasized in the literature discussed in Chapter 2) the most important factor behind firms' choices about technology developments. In this case, the spillover effects we emphasize can be of second order only. It is, however, worth to

[3] As observed by Acemoglu (2002a), this is often the case in less developed countries where, because of lack of intellectual property rights, new machine varieties invented in the North of the world can be copied without paying royalties.

emphasize that there are many circumstances in which already available technologies are not adopted by firms and adoption/adjustment costs are just not big enough to explain why. These are the cases in which the strategic interactions developed in this dissertation are likely to be important.

The firm solves the following profit maximization problem subject to the participation and non-shirking constraints of workers:

$$\max_{N,T,w} \quad \Pi = \Phi(N,T) - wN$$
$$\text{s.t.} \quad V^{ns} \geq V^{s}, \quad V^{ns} \geq V_f(G), \quad V^{ns} \geq V_u,$$

where V^{ns}, V^{s}, $V_f(G)$ and V_u are defined respectively by Equations (5.3), (5.5), (5.10) and (5.7). The first constraint is the no-shirking constraint and the other two are the participation (individual rationality) constraints.

In solving the firm's decision problem, we consider two possible cases. In the first one that we denote as *Cournot-Nash*, the firm itself takes the externality it induces as a parameter given exogenously. In the second one, which we will refer to as *von Stackelberg case*, the firm knows the relationship between the technology it adopts and the production externality it induces and takes it into account while solving its profit maximization problem. In particular, we assume g to be increasing in T, so that the technology adopted by the firm increases the workers' productivity in the self-employment sector of the economy. More precisely:

Assumption 5.6 *$g \in C^2$, $g(0) = 0$, $g'(T) > 0$, $\forall T \geq 0$.*

This assumption is meant to capture the positive impact of the spillover effects associated to the adoption of superior technologies. In this sense, although we do not develop a formal argument, the link between the technology operated in the market sector and the productivity of workers in the self-employment sector can be rationalized along the lines discussed in Section 4.2 of Chapter 4.

The following section introduces the benchmark case in which technology driven spillovers do not play any role, thus mimicking the behavior of the economy under perfect competition. This case, labeled above as *Cournot-Nash*, requires the firm to act myopically, ignoring the consequence of its (technology) choice on the actions of self-employed entrepreneurs.[4] In the next section we will then turn to the analysis of the more general case — that consistently with the previous one has been denoted above as *von Stackelberg case* — in which the strategic interaction between the firm and workers stemming from the technology driven externalities (i.e. the complementarity between technology and outside option) are relevant and affect the equilibrium outcome of the economy.

5.3 The Cournot-Nash case

We show that when the firm treats the externality as an exogenous parameter G and not as a function of technology its profit maximization problem is not constrained by it. We assume, for the sake of simplifying the analysis, that the Cournot firm assigns the same value as the self-employed to the externality, and start focusing on the workers' individual rationality and incentive compatibility constraints. Assuming different evaluations of the externality might have an impact on the firm's ability to satisfy labor demand. This would be the case if its valuation of the externality is lower than the one by the self-employed. Insofar an higher externality transfers into a better outside option, the wage offer by the firm would not be enough to satisfy a self-employed's participation constraint. This would imply complete rationing of the firm on the labor market. In a framework of complete information, it seems natural to assume that the firm is knowledgeable about the outside options available

[4] This is a type of bounded rationality in that the firm is assumed to be unable to contemplate the strategic implications of its action.

to self-employed agents and thus it takes the relevant externalities into account when designing its wage offer.

Using (5.3), (5.5) and (5.10), the firm's constraints $V^{ns} \geq V^s$ and $V^{ns} \geq V_f(G)$ can be written respectively as

$$w \geq e/c, \tag{5.11}$$

$$w \geq W_f(G) + e - \varphi(h_f(G)). \tag{5.12}$$

There is no need to focus on the constraint $V^{ns} \geq V_u$ (i.e. $w \geq e$) since, being $0 < c < 1$, it is satisfied whenever the no-shirking constraint (5.11) is satisfied. It is obviously in the firm's interest to make w as small as possible, while satisfying (5.11) and (5.12). Hence, these constraints are to be taken as binding and written in compact form as

$$W(G) := \max \left\{ \frac{e}{c}, W_f(G) + e - \varphi(h_f(G)) \right\}. \tag{5.13}$$

where W denotes the lowest wage compatible with the no-shirking and participation constraints.[5]

Notice that the actual externality level will be determined in equilibrium. Given G, the firm's decision problem is[6]

$$\left\{ \begin{array}{l} \max_{N,T,w} \quad \Pi = \Phi(N,T) - wN \\ s.t. \quad w \geq \max \quad \left\{ \frac{e}{c}, W_f(G) + e - \varphi(h_f(G)) \right\} \end{array} \right. . \tag{5.14}$$

We already know from the discussion of Equation (5.13) that the constraint in Problem (5.14) is binding. By Assumption 5.4, $\Phi(N,T)$ is an increasing function in T. Hence, from Problem (5.14), it follows immediately that the Cournot firm chooses to adopt the technology $T_{\max}$. This

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[5] In the special case in which labor time is the same both when a consumer is self-employed or employed by the firm, i.e. $h = h_f(G)$, constraint (5.13) simplifies to

$$W = \max \left\{ \frac{e}{c}, Gh_f(G) \right\},$$

where $e = \varphi(h) = \varphi(h_f(G))$.

[6] We denote with w the generic wage level, and with W the wage level at the equilibrium.

implies that labor demand follows from the first order condition of Problem (5.14) for an interior solution

$$\frac{\partial \Phi\left(N, T_{\max}\right)}{\partial N} = W\left(G\right) := \max \quad \left\{\frac{e}{c}, W_f\left(G\right) + e - \varphi\left(h_f\left(G\right)\right)\right\}, \tag{5.15}$$

which gives, by Assumption 5.4, $\hat{N}\left(T_{\max}, W\left(G\right)\right)$ as a unique solution.

We assume throughout

Assumption 5.7 *$\bar{N}$ is sufficiently large so that $\hat{N} < \bar{N}$ for all admissible parameters values.*

This is a technical assumption to avoid the possibility of rationing of labor demand by the firm that has no impact on the generality of our results. By marking the equilibrium allocations with C, we can now define a *Cournot equilibrium* as follows.

Definition 5.1 *Given parameters e, c, $\bar{N}$ and $T_{\max}$, a triple $\{w^C, w_f^C, \pi^C\}$, a technology $T^C \geq 0$, employment levels $N^C \geq 0$, $N_f^C \geq 0$, $N_u^C \geq 0$, and an externality level G^C constitute a Cournot equilibrium if the following conditions are fulfilled:*

(1) $w^C = W(G^C)$,

(2) $w_f^C = W_f(G^C) = G^C h_f(G^C)$,

(3) $\pi^C = \Pi^C / \bar{N}$, *where* $\Pi^C = \Phi(N^C, T^C) - w^C N^C$,

such that

(4) $T^C \leqq T_{\max}$,

(5) $N^C = \hat{N}\left(T^C, W(G^C)\right), \quad N_f^C = \bar{N} - N^C, \quad N_u^C = 0$,

(6) $G^C = g(T^C)$

hold.

Existence and uniqueness of the Cournot equilibrium follow immediately from the above discussion. Conditions (1) and (2) follow directly from Equations (5.13) and (5.9) respectively. Condition (3) derives from the profit distribution scheme introduced by Assumption 5.2. T^C and N^C

solve Problem (5.14), from which it is apparent that $T^C = T_{\max}$; and the values N_f^C and N_u^C follow from the fact that all workers not employed by the firm prefer to work as self-employed instead of remaining unemployed since $V_f^C > V_u^C$. Finally, given Assumption 5.6, in equilibrium it must be $G^C = g(T^C)$, as stated by Condition(6).

Notice that albeit we adopt an efficiency wage setup there is always full employment in equilibrium since workers not hired by the firm have the option to work as self employed. Notice as well that in equilibrium all workers employed by the firm are non-shirkers, since the wage paid by the firm satisfies the workers' incentive compatibility constraint. Moreover, given that the externality is treated as an exogenous parameter, there is no inefficiency in the technology adoption process as the firm does always adopt the best available technology. Since $T^C = T_{\max}$, in equilibrium the firm fails to internalize all the externalities it generates neglecting their impact, so that the first best outcome is achieved. In this sense, the analysis of technology adoption under our Cournot-Nash scenario achieves the same equilibrium and shares the same properties that would be attained in a perfectly competitive framework.

5.4 The von Stackelberg case

We now turn to the von Stackelberg case, in which the firm considers the strategic reaction of self-employed entrepreneurs in its response function.[7] We show that allocative inefficiencies may arise that were absent in the Cournot benchmark case.

The externality producer firm does take into account the impact of its technology choice on the externality it induces. By Assumption 5.6,

[7] Implicit in the von Stackelberg formulation is a *staggering* issue, as if one agent chooses ahead of the other: the forward looking firm internalizes the response of self-employed entrepreneurs in its optimal "reaction function".

the individual rationality and incentive compatibility constraints faced by the von Stackelberg firm require that

$$w \geq \max \quad \left\{ \frac{e}{c}, g\left(T\right) h_f\left(g\left(T\right)\right) + e - \varphi\left(h_f\left(g\left(T\right)\right)\right) \right\}. \tag{5.16}$$

Hence, the firm's decision problem can be written as[8]

$$\begin{cases} \max\limits_{N,T,w} \quad \Pi = \Phi\left(N,T\right) - wN \\ s.t. \;\; w \geq \max \quad \left\{ \frac{e}{c}, g\left(T\right) h_f\left(g\left(T\right)\right) + e - \varphi\left(h_f\left(g\left(T\right)\right)\right) \right\} \end{cases}. \tag{5.17}$$

By focusing on Constraint (5.16), given the assumptions made, namely $e > 0$, Assumption 5.6 and Assumption 5.1, it is immediate to see that

$$W\left(g\left(T\right)\right) := \begin{cases} e/c, & T \in [0, \tilde{T}), \\ g(T)h_f(g(T)) - \varphi(h_f(g(T))) + e, & T \in [\tilde{T}, T_{\max}], \end{cases} \tag{5.18}$$

where $\tilde{T}$ solves the following equation in T

$$\frac{e}{c} = g(T)h_f(g(T)) - \varphi\left(h_f(g(T))\right) + e. \tag{5.19}$$

[8] Problem (5.17) simplifies further in the special case in which labor time (and hence disutility of effort) is the same for both self-employed entrepreneurs and workers employed by the firm. In fact, in this case, Constraint (5.16) becomes

$$w \geq \max \left\{ \frac{\varphi\left(h_f\left(g\left(T\right)\right)\right)}{c}, g\left(T\right) h_f\left(g\left(T\right)\right) \right\}.$$

Both expressions into brackets are increasing in T and equal to 0 for $T = 0$. By differentiating them we get, respectively

$$\varphi'\left(h_f\left(g\left(T\right)\right)\right) \frac{dh_f\left(.\right)}{dg} \frac{dg\left(T\right)}{dT} > 0, \qquad g\left(T\right) \frac{dh_f\left(.\right)}{dg} \frac{dg\left(T\right)}{dT} + \frac{dg\left(T\right)}{dT} h_f\left(g\left(T\right)\right) > 0.$$

Recalling that from the first order condition of Problem (5.8) it is $g = \varphi'\left(.\right)$ and given the assumptions made on $g\left(.\right)$ and $h\left(.\right)$, the expression in the second inequality above is always greater than the first one for all T greater than zero. Therefore, without loss of generality, one can write $W\left(T\right) = g\left(T\right) h_f\left(g\left(T\right)\right)$. Thus, the leader's problem simplifies to

$$\max_{N,T} \Pi = \Phi\left(N,T\right) - W\left(T\right) N$$

By studying this problem, we get results that are qualitatively equivalent to those obtained for the general case.

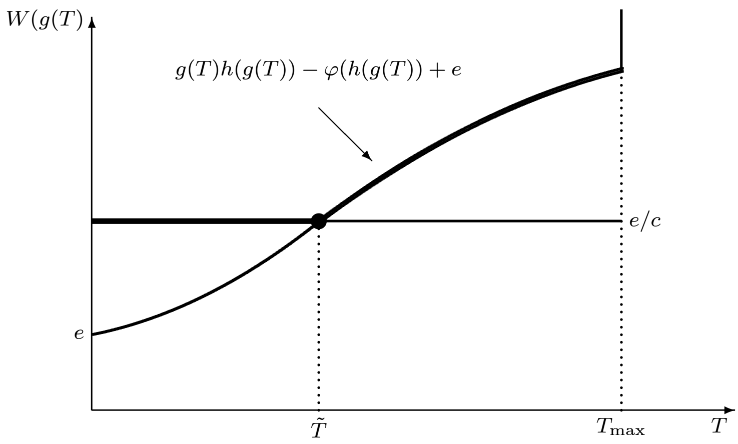

FIGURE 5.1. Wage setting by the leader

If it exists, it is $\tilde{T} > 0$ and unique since the right hand side of Equation (5.19) is equal to $e < e/c$ at $T = 0$ and then is strictly increasing for $T > 0$.[9]

In order to rule out uninteresting cases we assume that parameters c, e and $T_{\max}$ are such that

Assumption 5.8 $\tilde{T} < T_{\max}$.

It is immediate to observe that if Assumption 5.8 does not hold, the firm can always satisfy both the workers' individual rationality and incentive compatibility constraints by setting $W(g(T)) = e/c$, implying that technology spillovers would never influence the firm's wage setting.

Equation (5.18) is illustrated in Figure 5.1. Up to $\tilde{T}$, technological spillovers are irrelevant for wage setting, since the dominant effect is represented by the need to offer the no-shirking efficiency wage. Above $\tilde{T}$, on the contrary, technological spillovers become the main determinant of wage setting by the firm.

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[9] The first derivative of the right hand side is $g'(T) h_f(g(T)) + g(T) \frac{dh_f(.)}{dg(T)} g'(T) - \varphi'(h_f(g(T))) \frac{dh_f(.)}{dg(T)} g'(T)$, which reduces to $g'(T) h_f(g(T)) > 0$ since $g(T) = \varphi'(h_f(g(T)))$ from the first order condition of Problem (5.8). The fact that the firm exploits the latter property of $g(T)$ amounts implicitly to assume common knowledge of the economy's structure.

Before proceeding, it is worth stressing the impact of the workers' effort level and of the firm's monitoring (expressed in terms of the probability c) on the threshold technology grade $\tilde{T}$. By implicitly differentiating Equation (5.19) and after some algebra, we get

$$\frac{d\tilde{T}}{de} = \left(\frac{1}{c} - 1\right) \frac{1}{g'(T)\, h_f(g(T))} > 0$$

and

$$\frac{d\tilde{T}}{dc} = -\frac{e}{c^2} \frac{1}{g'(T)\, h_f(g(T))} < 0.$$

The technology level at which externalities start becoming relevant in the firm's wage setting is thus increasing in the effort exerted by workers and decreasing in the monitoring by the firm. The intuition behind these results is that the higher the level of effort required to workers, the higher is the wage necessary to satisfy their incentive compatibility constraint regardless of the technology operated by the firm. In this sense, an increase in effort mitigates the direct impact of spillovers. Conversely, a better monitoring has exactly the opposite effect. An increase in the probability that a shirker is caught shirking reduces the wage that the firm must pay in order to satisfy the workers' incentive compatibility constraint independently of the technology used.

We can now define a *von Stackelberg equilibrium* as follows.

Definition 5.2 *Given parameters* e, c, $\bar{N}$ *and* $T_{\max}$, *a triple* $\{w^*, w_f^*, \pi^*\}$, *a technology* T^*, *employment levels* $N^* \geq 0$, $N_f^* \geq 0$, $N_u^* \geq 0$ *and an externality level* g^* *constitute a von Stackelberg equilibrium if*

(1) (N^*, T^*, w^*) *is a solution of Problem (5.17),*

(2) $w^* = W(g^*)$,

(3) $w_f^* = g^* h_f(g^*) = g^* h_f^*$,

(4) $\pi^* = \Pi^*/\bar{N}$, *where* $\Pi^* = \Phi(N^*, T^*) - w^* N^*$,

such that

(5) $N^* = \hat{N}(T^*, w^*)$, $N_f^* = \bar{N} - N^*$ *and*

(6) $g^* = g(T^*)$

hold.

In order to discuss the *existence* and *uniqueness* of the von Stackelberg equilibrium, we concentrate on Problem (5.17). From Equation (5.18), one can see that $W(g(T))$ is continuous in T in the relevant range $[0, T_{\max}]$ but presents a kink at $T = \tilde{T}$; hence, its derivative $dW(g(T))/dT$ is discontinuous at this point, jumping from $dW(g(T))/dT|_{T\to\tilde{T}^-} = 0$ to $dW(g(T))/dT|_{T\to\tilde{T}^+} = g'(\tilde{T})h_f(\tilde{T}) > 0$. Formally,

$$\frac{dW(g(T))}{dT} = \begin{cases} 0, & T \in [0,\tilde{T}) \text{ and } T \to \tilde{T}^- \\ g'(T)h_f(T), & T \in (\tilde{T}, T_{\max}] \text{ and } T \to \tilde{T}^+ \end{cases}. \tag{5.20}$$

Substituting for $W(g(T))$ into the firm's profit function, Problem (5.17) becomes

$$\max_{N,T} \quad \Pi = \Phi(N,T) - W(g(T))\,N. \tag{5.21}$$

Consider first the choice of labor input, given T. The first order condition for an interior solution is

$$\frac{\partial \Pi}{\partial N} = \frac{\partial \Phi(N,T)}{\partial N} - W(g(T)) = 0, \tag{5.22}$$

which gives, by Assumption 5.4, $\hat{N}(T,W)$ as a unique solution.[10]

By totally differentiating (5.22) we get[11]

$$\frac{\partial \hat{N}(T,W)}{\partial T} = \left(\frac{dW}{dT} - \frac{\partial^2 \Phi}{\partial N \partial T}\right) \Big/ \frac{\partial^2 \Phi}{\partial N^2}. \tag{5.23}$$

For $T \in [0,\tilde{T})$, (5.23) is positive whenever $\frac{\partial^2 \Phi}{\partial N \partial T} > 0$, since $\frac{dW}{dT} = 0$ and $\frac{\partial^2 \Phi}{\partial N^2} < 0$. In words, technology adoption brings about higher labor demand if a better technology augments the marginal productivity of labor. The relation between labor demand and technology adoption is less clear-cut when $T \in [\tilde{T}, T_{\max}]$. In this case, a better technology increases,

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[10] The possibility of rationing of labor demand by the firm is ruled away by Assumption 5.7.

[11] In order to save on notation, we write W instead of $W(g(T))$ and g instead of $g(T)$ whenever this is not misleading.

via the spillover effect, the wage the firm must pay ($dW/dT > 0$), and this tends to reduce labor demand. Hence, if $\frac{\partial^2 \Phi}{\partial N \partial T} > 0$ the overall effect is ambiguous, whereas if $\frac{\partial^2 \Phi}{\partial N \partial T} < 0$ then (5.23) is negative.

Substituting labor demand $\hat{N}(T, W)$ into the profit function (5.21), the problem of optimal technology adoption can now be written as

$$\max_{T} \quad \hat{\Pi}\left(T, W\right) = \Phi(\hat{N}\left(T, W\right), T) - W\hat{N}\left(T, W\right). \tag{5.24}$$

By differentiating, we have that

$$\frac{\partial \hat{\Pi}\left(T, W\right)}{\partial T} = \begin{cases} \dfrac{\partial \Phi(\hat{N}, T)}{\partial T}, & T \in [0, \tilde{T}) \text{ and } T \to \tilde{T}^{-} \quad \text{(a)} \\ \dfrac{\partial \Phi(\hat{N}, T)}{\partial T} - \hat{N}\dfrac{dW}{dT}, & T \in (\tilde{T}, T_{\max}] \text{ and } T \to \tilde{T}^{+} \quad \text{(b)} \end{cases}. \tag{5.25}$$

Since $\partial \Phi / \partial T > 0$, (5.25a) is strictly positive and hence the optimal level of technology adoption, T^{*}, is never lower than $\tilde{T}$. In other words, it always pays to expand technology as long as spillovers are irrelevant. Whether or not it is desirable to go further in the process of technology adoption it all depends on the sign of (5.25) for $T \to \tilde{T}^{+}$ and on its behavior for $T > \tilde{T}$. As for the sign of $\left.\frac{\partial \hat{\Pi}}{\partial T}\right|_{T \to \tilde{T}^{+}}$, from (5.25b) and (5.20), this is clearly ambiguous, as $\frac{\partial \Phi(\hat{N}, T)}{\partial T} > 0$ and $\frac{dW}{dT} > 0$. In words, it is positive if the marginal productivity of technology adoption is greater than marginal labor costs induced by the spillover effect, whereas it is negative when the latter effect dominates the former. As for the behavior of $\left.\frac{\partial \hat{\Pi}}{\partial T}\right|_{T > \tilde{T}}$, it is characterized by the following equation, obtained by differentiating (5.25b):

$$\frac{\partial^2 \hat{\Pi}}{\partial T^2} = \frac{\partial^2 \Phi}{\partial T^2} - \frac{\partial^2 \Phi}{\partial N^2}\left(\frac{\partial \hat{N}}{\partial T}\right)^2 - \hat{N}\frac{d^2 W}{dT^2}, \qquad T \in (\tilde{T}, T_{\max}], \tag{5.26}$$

where we have used (5.23) and the symmetry of cross partial derivatives of $\Phi(.)$ to obtain the second term.[12] The sign of Equation (5.26) depends on the sign of three terms. The first is negative (positive) whenever there are decreasing (increasing) returns in technology adoption. The second term is always positive, since we have assumed decreasing returns in labor inputs. Finally, the sign of the third term is ambiguous. A sufficient condition for it to be negative is that $g'' > 0$, meaning that technology adoption by the externality producer has an increasing marginal spillover effect on the self-employed productivity, since in this case $\frac{d^2W}{dT^2} = g''h_f + g'\frac{dh_f}{dT} > 0$. If, on the other hand, $g'' < 0$, the sign of $\frac{d^2W}{dT^2}$, and hence that of the third term in (5.26), remains undetermined. Clearly, the overall sign of (5.26) is an empirical matter, as there are no theoretical explanations that can help to show which one of the three effects dominates over the others.[13]

In order to ensure a unique solution to the problem of technology adoption by the firm, it is sufficient to impose the following

Assumption 5.9 $\partial\hat{\Pi}/\partial T$ *is monotone.*

In principle, one could argue that the impact of technology on profits is a function of the specific technology grade adopted. For example, spillovers can be completely irrelevant until a certain threshold technology. This, however, does not seem restrictive in the present framework. In fact, it is enough that the "regularity" Assumption 5.9 holds to restrict

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[12] More precisely, from (5.25) it is

$$\begin{aligned}\frac{\partial^2\hat{\Pi}}{\partial T^2} &= \frac{\partial^2\Phi}{\partial T^2} + \frac{\partial^2\Phi}{\partial T\partial N}\frac{\partial\hat{N}}{\partial T} - \hat{N}\frac{d^2W}{dT^2} - \frac{\partial\hat{N}}{\partial T}\frac{dW}{dT} = \\ &\frac{\partial^2\Phi}{\partial T^2} - \left(\frac{dW}{dT} - \frac{\partial^2\Phi}{\partial T\partial N}\right)\frac{\partial\hat{N}}{\partial T} - \hat{N}\frac{d^2W}{dT^2},\end{aligned}$$

and by making use of (5.23), we obtain Equation (5.26).

[13] The solution of our two-step maximization — Problem (5.21) with T fixed and then Problem (5.24)— is equivalent to the first order conditions of Problem (5.21), since Derivative (5.26) equals to (minus) the determinant of the Hessian matrix for Problem (5.21) and $\partial^2\Phi/\partial N^2 < 0$.

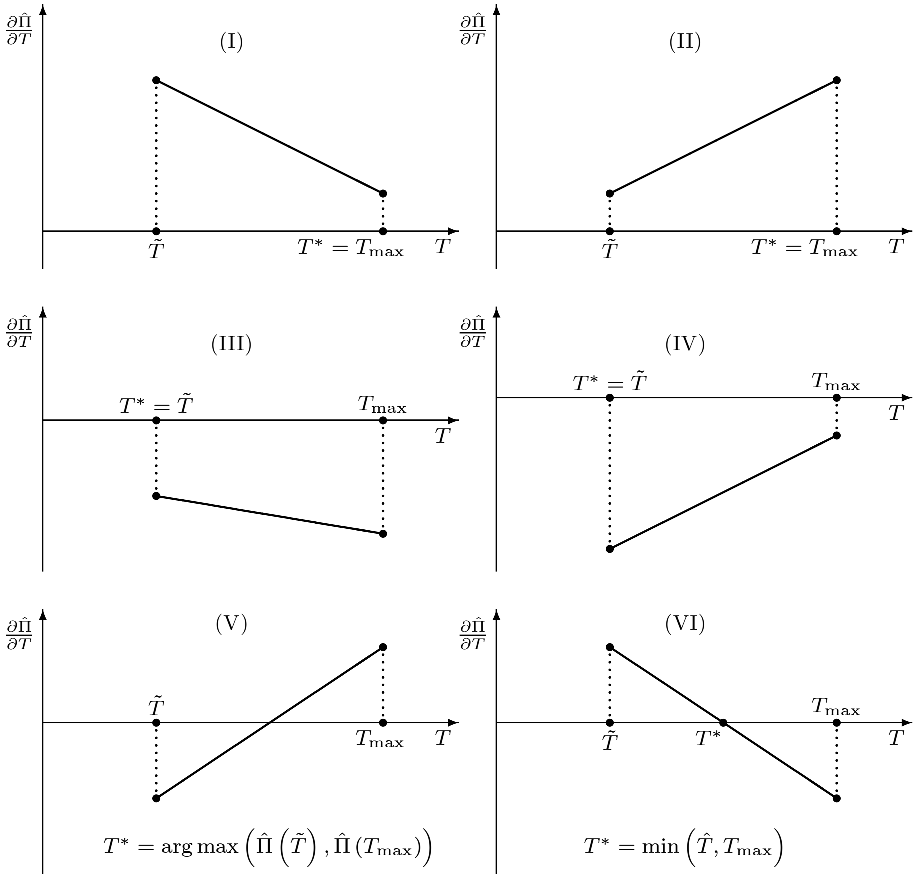

FIGURE 5.2. Optimal technology adoption

Equation (5.26) to have the same sign over the interval $(\tilde{T}, T_{\max}]$.This amounts to require that the marginal impact of technology on profits keeps going in the same direction as the technology grade improves, in the interval where production externalities are potentially relevant.

Under Assumption 5.9, the optimal T is then characterized by the signs of partial derivatives (5.25b) and (5.26). By Assumption 5.9, there are four possible cases that may arise, each with a unique optimal T, which are depicted in Figure 5.2. In the first one, it is either $\left.\frac{\partial \hat{\Pi}}{\partial T}\right|_{T \to \tilde{T}^+} > 0$, $\left.\frac{\partial \hat{\Pi}}{\partial T}\right|_{T = T_{\max}} > 0$ and $\left.\frac{\partial^2 \hat{\Pi}}{\partial T^2}\right|_{T > \tilde{T}} \leq 0$ (panel I) or $\left.\frac{\partial \hat{\Pi}}{\partial T}\right|_{T \to \tilde{T}^+} > 0$ and

$\left.\frac{\partial^2\hat{\Pi}}{\partial T^2}\right|_{T>\tilde{T}} \geq 0$ (panel II), hence $T^* = T_{\max}$. Spillovers are weak so that the firm always adopts the best available technology (*technological frontier regime*). In the second one, it is either $\left.\frac{\partial\hat{\Pi}}{\partial T}\right|_{T\to\tilde{T}+} < 0$ and $\left.\frac{\partial^2\hat{\Pi}}{\partial T^2}\right|_{T>\tilde{T}} \leq 0$ (panel III) or $\left.\frac{\partial\hat{\Pi}}{\partial T}\right|_{T\to\tilde{T}+} < 0$, $\left.\frac{\partial\hat{\Pi}}{\partial T}\right|_{T=T_{\max}} < 0$ and $\left.\frac{\partial^2\hat{\Pi}}{\partial T^2}\right|_{T>\tilde{T}} \geq 0$ (panel IV), hence $T^* = \tilde{T}$. Spillovers are so important to eliminate any incentive for the firm to adopt a superior technology and therefore technology adoption stops at $\tilde{T}$ (*blocked adoption regime*). In the third one $\left.\frac{\partial\hat{\Pi}}{\partial T}\right|_{T\to\tilde{T}+} < 0$, $\left.\frac{\partial\hat{\Pi}}{\partial T}\right|_{T=T_{\max}} > 0$ and $\left.\frac{\partial^2\hat{\Pi}}{\partial T^2}\right|_{T>\tilde{T}} > 0$ (panel V), so that $T^* = \arg\max_T \left(\hat{\Pi}\left(\tilde{T}\right), \hat{\Pi}\left(T_{\max}\right)\right)$. Spillovers are relevant, but they may be dominated by increased productivity in the firm's sector. Finally, in the last case (a possible outcome of which, corresponding to the case $\left.\frac{\partial\hat{\Pi}}{\partial T}\right|_{T=T_{\max}} < 0$, is shown in panel VI) it is $\left.\frac{\partial\hat{\Pi}}{\partial T}\right|_{T\to\tilde{T}+} > 0$ and $\left.\frac{\partial^2\hat{\Pi}}{\partial T^2}\right|_{T>\tilde{T}} < 0$, hence $T^* = \min(\hat{T}, T_{\max})$, where $\hat{T} > \tilde{T}$ solves the first order condition

$$\frac{\partial\hat{\Pi}}{\partial T} = \frac{\partial\Phi(\hat{N}, T)}{\partial T} - \hat{N}\frac{dW}{dT} = 0. \tag{5.27}$$

Spillovers are important, but not so as to prevent the adoption of a superior technology by the firm, although not necessarily the one at the frontier. Notice that the above conditions for the last case do not guarantee that the technology adopted by the firm is not the one at the technology frontier either, i.e. $T^* = \hat{T} \in (\tilde{T}, T_{\max})$, a case to which we will refer to as *spillover regime*. It is, however, immediate to observe that a necessary and sufficient condition for this case to occur is to require that $\left.\frac{\partial\hat{\Pi}}{\partial T}\right|_{T=T_{\max}} < 0$ and $\left.\frac{\partial\hat{\Pi}}{\partial T}\right|_{T\to\tilde{T}+} > 0$. This, combined with Assumption 5.9 on the monotonicity of $\partial\hat{\Pi}/\partial T$ — ensuring that there is one and only one T such that $\frac{\partial\hat{\Pi}}{\partial T} = 0$ —, guarantees that $\hat{T} \in (\tilde{T}, T_{\max})$ is the

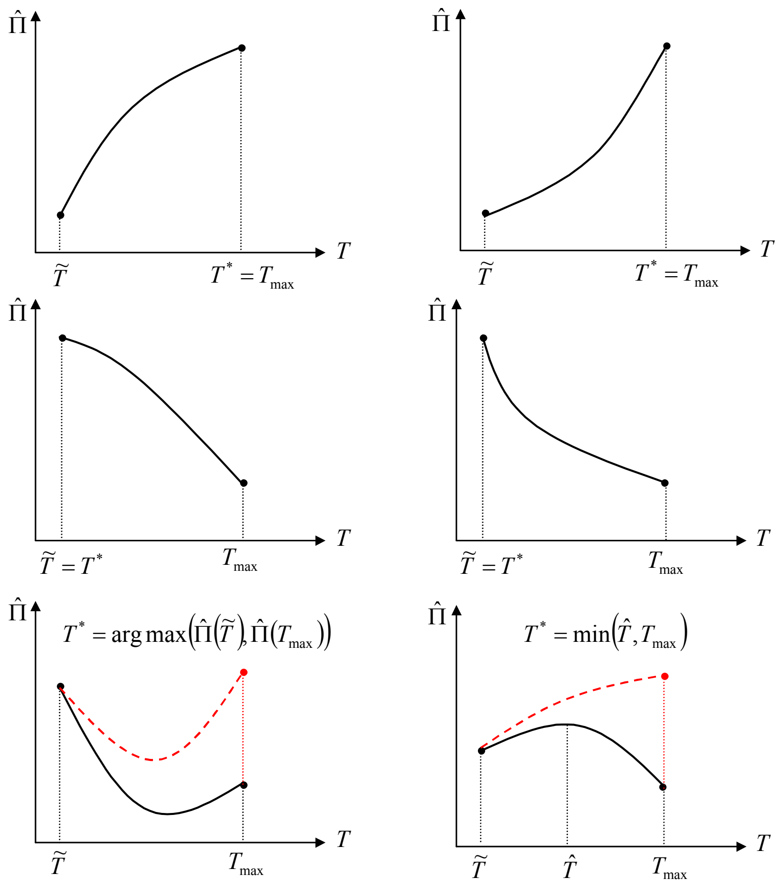

FIGURE 5.3. The firm's profit function

unique solution of the firm technology choice problem.[14] Figure 5.3 illustrates the shape of the firm's profit function and the technology chosen for all the cases represented in Figure 5.2.

The above discussion is summarized by the following proposition.

Proposition 5.1 *Under Assumptions 5.6 – 5.9, the technology chosen by the firm is unique. Any one of the following three regimes may arise:*

1. *Blocked adoption regime:* $T^* = \tilde{T}$*;*

[14] Assumption 5.9 on the monotonicity of the profit function is not necessary. In Section 5.5.2, we consider an example for a Cobb-Douglas economy, deriving a technology spillover regime without imposing any restriction on the sign of the second derivative of $\hat{\Pi}(T)$.

2. *Technological frontier regime:* $T^* = T_{\max}$*;*

3. *Spillover regime:* $T^* = \hat{T} \in (\tilde{T}, T_{\max})$*.*

The three graphs in Figure 5.4 — depicting in the $(W(g(T)), T)$-space the firm's profit contours and the (incentive compatibility and individual rationality) constraint on wages it faces — illustrate the choice of technology by the firm under the three regimes identified in Proposition 5.1: spillover regime (graph a), technological frontier (graph b) and blocked adoption (graph c).

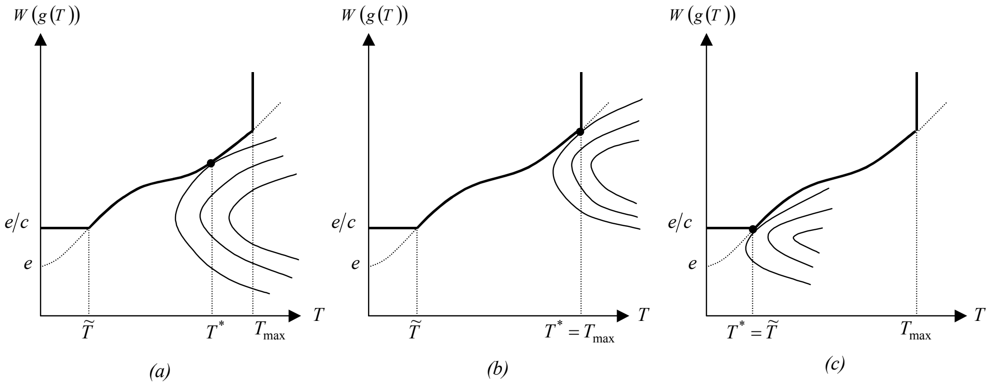

FIGURE 5.4. The firm's technology choice

Proposition 5.1 identifies the unique T^* solving Problem (5.17) and characterizes the different types of (unique) equilibria possibly arising in our economy. Given T^*, w^* is uniquely defined by Equation (5.18), and $N^* = \hat{N}(T^*, w^*)$. Furthermore, the unique equilibrium values $g^* = g(T^*)$, w_f^* and π^* follow from Assumption 5.6, Equation (5.9) and Assumption 5.1, and Assumption 5.2 respectively. Notice also that in the von Stackelberg case, albeit the presence of an efficiency wage in the market sector guaranteeing that the firm does not employ shirkers, in equilibrium there is always full employment, since workers not hired by the firm have an incentive to make an earning with self employment, where they never shirk.[15] This follows directly from Assumption 5.3 and by inspection of Equation (5.10). Hence, at the von Stackelberg equilibrium, $N^* = \hat{N}(T^*, w^*)$, $N_f^* = \bar{N} - N^* \geq 0$, and $N_u^* = 0$. Notice, also, that whenever superior technologies are labor saving the number of workers hired by the firm will be higher in the von Stackelberg than in the Cournot equilibrium. In the latter regime, in fact, it will always be $T^C = T_{\max}$ at the equilibrium. This amounts to say that, although in both cases there is no unemployment in equilibrium, there is a different distribution of workers between the market sector and the self-employment sector of the economy under the von Stackelberg and the Cournot-Nash regimes, with lower employment in the market sector under the latter.

Finally, a subtle point is worth noting. Throughout the dissertation we assume that the firm's monitoring is not affected by the choice of technology. However, one could argue that the adoption of a higher grade technology may have an impact on the firm's ability to detect shirkers, influencing monitoring costs. This, in turn, would affect the incentive compatibility constraint and hence the wage the firm must pay to workers. In this sense, the impact of technology adoption on monitoring can either reinforce or weaken its effect on the workers' outside options (captured by their productivity as self-employed entrepreneurs). In the case that better technologies improve monitoring, for our argument to affect firms' decisions (by increasing wages), it is necessary that the impact of technology adoption on incentive compatibility (i.e. on the probability to be caught shirking) is of second order with respect to that on individual rationality.

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[15] Recall that we refer to the firm's labor market with the expression "market sector", as opposed to "self-employment sector".

5.5 An example: Cobb-Douglas Economy

In this section, we extend the Cobb-Douglas partial equilibrium framework developed in Chapter 4 to the general equilibrium economy studied in this chapter and we use it to perform comparative statics exercises. In order to do so, we describe the (technology-induced) production externality by letting

$$g(T) := T^{\gamma}, \tag{5.28}$$

and we model the self-employed entrepreneurs (workers) labor disutility by assuming

$$\varphi(h_f) := h_f^2/2. \tag{5.29}$$

The firm's production function is described by Equation (4.17) in Section 4.5 of Chapter 4, i.e. $\Phi(N,T) = T^{\alpha}N^{\beta}$, and the Assumptions 4.5 - 4.7 made there continue to hold. All notation remains as in the previous sections and, whenever without ambiguities, we will slightly abuse it in order to ease the exposition. As it has been the case for the partial equilibrium application to the Cobb-Douglas economy, we stress again that the Assumptions 4.5 and 4.6 on α, β and γ account for a subset only of the cases that can emerge in the general equilibrium framework studied in the previous sections of the chapter.

5.5.1 The Cournot-Nash case

In the Cournot-Nash case, the firm behaves as the self-employed entrepreneurs, in that it takes the externality as a given parameter (i.e. it does not take into account the impact of its decisions on the externality level). We denote, without loss of generality, this externality level with G. Following the discussion in Section 5.3, the firm's decision problem can be written as

$$\begin{cases} \max\limits_{N,T,w} & \Pi(N,T) = T^{\alpha}N^{\beta} - wN \\ s.t. \;\; w \geq \max & \left\{\frac{e}{c}, Gh_f(G) + e - \frac{h_f(G)^2}{2}\right\} \end{cases}.$$

Since $\Pi(N,T)$ is increasing in T the profit maximizing technology adopted by the Cournot firm is $T^C = T_{\max}$. As for the optimal wage, we already know that the constraint in the above maximization problem is always binding and therefore it is

$$w^C = W(G) = \max \left\{\frac{e}{c}, Gh_f(G) + e - \frac{h_f(G)^2}{2}\right\}.$$

Finally, given $T^C = T_{\max}$, the employment level is determined by the first order condition

$$\beta T_{\max}^{\alpha} N^{C\beta-1} = W(G),$$

and thus

$$N^C = \left(\frac{W(G)}{\beta T_{\max}^{\alpha}}\right)^{\frac{1}{\beta-1}}. \tag{5.30}$$

It is immediate to see that externalities do not play any role in the choice of technology by the firm. On the other hand, they do affect parametrically the equilibrium level of wage and hence the firm's employment.

5.5.2 The von Stackelberg case

We now apply to the Cobb-Douglas economy the analysis of the von Stackelberg case studied in Section 5.4. In this scenario, the firm does take into account the impact of the externalities it generates through its technology choice. Knowing the labor choice of the self-employed, $h_f = g(T)$,[16] and substituting for $g(T) = T^{\gamma}$, the decision problem of self-employed entrepreneurs/workers (Equation (5.8) in Section 5.2.2) yields

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[16] $h_f := \arg\max g(T) h_f - \frac{h_f^2}{2}$.

$h_f = T^{\gamma}$, and hence the corresponding utility level of a self-employed is

$$\hat{V}_f = \frac{T^{2\gamma}}{2} + \pi.$$

Given the specific functional forms we consider, the workers' participation and incentive compatibility constraint (Equation (5.13)) becomes

$$W(T) = \max \left\{ \frac{e}{c}, \frac{T^{2\gamma}}{2} + e \right\} \tag{5.31}$$

and the decision problem faced by the firm is

$$\max_{T,N,w} \quad \Pi = T^{\alpha} N^{\beta} - wN \tag{5.32}$$
$$\text{s.t.} \qquad w = \max \left\{ \frac{e}{c}, \frac{T^{2\gamma}}{2} + e \right\}.$$

The technology threshold $\tilde{T}$ — at which externalities start becoming relevant — follows immediately by solving

$$\frac{T^{2\gamma}}{2} + e = \frac{e}{c},$$

i.e.

$$\tilde{T} = \left(\frac{2e(1-c)}{c} \right)^{\frac{1}{2\gamma}}. \tag{5.33}$$

Since Π is monotonically increasing in T for $T \in [0, \tilde{T})$ and for any N, it is $T^* \geqq \tilde{T}$. Hence, the optimal level of technology is never lower than $\tilde{T}$. In order to understand if and when it pays to expand technology over $\tilde{T}$ when $T \in (\tilde{T}, T_{\max}]$, we need to study the sign of $\frac{\partial \Pi}{\partial T}$ for $T \to \tilde{T}^{+}$ and its behavior for $T > \tilde{T}$. From the first order condition with respect to N, given $T \in (\tilde{T}, T_{\max}]$, of Problem (5.32) it is immediate to get

$$\hat{N}(T) = \left(\frac{\frac{T^{2\gamma}}{2} + e}{\beta T^{\alpha}} \right)^{\frac{1}{\beta - 1}}. \tag{5.34}$$

By differentiating Problem (5.32) with respect to T, and using $\hat{N}(T)$, one obtains

$$\frac{\partial \hat{\Pi}\left(\hat{N}(T), T\right)}{\partial T} = \alpha T^{\alpha-1} \hat{N}^{\beta} - \gamma T^{2\gamma-1} \hat{N} \quad T \in (\tilde{T}, T_{\max}] \text{ and } T \to \tilde{T}^{+}. \tag{5.35}$$

By applying Proposition 5.1, we know that two regimes are possible when it pays to expand technology over $\tilde{T}$: either the firm adopts the best available technology (i.e. the technological frontier case in which $T^* = T_{\max}$) or it improves its technology, but not up to the frontier (i.e. the spillover case, with $T^* = \hat{T} \in (\tilde{T}, T_{\max})$).[17] In order to determine $\hat{T}$ in the latter regime, by substituting $\hat{N}(T)$ into Equation (5.35) and after some algebra, it is

$$\left(\frac{\frac{T^{2\gamma}}{2}+e}{\beta T^{\alpha}}\right)^{\frac{1}{\beta-1}}\left[\frac{\alpha\left(T^{2\gamma}/2+e\right)}{\beta T}-\gamma T^{2\gamma-1}\right]=0,$$

from which, being $T \neq 0$, it is[18]

$$\hat{T}=\left(\frac{2\alpha e}{2\beta\gamma-\alpha}\right)^{\frac{1}{2\gamma}}. \tag{5.36}$$

In general, for a technology spillover regime to emerge, by applying the logic behind Proposition 5.1 — whose assumptions are satisfied by the Cobb-Douglas economy under exam — we need to require that $\frac{\partial \hat{\Pi}}{\partial T}\mid_{T\to\tilde{T}^+}>0$ and $\frac{\partial \hat{\Pi}}{\partial T}\mid_{T=T_{\max}}<0$ are simultaneously satisfied. More precisely, following the logic of Proposition 5.1, since $\hat{\Pi}(T) \in \mathcal{C}^2$ in $(\tilde{T}, T_{\max}]$ and there exists a unique $\hat{T}$ — given by Equation (5.36) — such that $\frac{\partial \hat{\Pi}(\hat{T})}{\partial T}=0$, requiring that the two conditions $\frac{\partial \hat{\Pi}}{\partial T}\mid_{T\to\tilde{T}^+}>0$ and $\frac{\partial \hat{\Pi}}{\partial T}\mid_{T=T_{\max}}<0$ hold guarantees that $\hat{T} \in (\tilde{T}, T_{\max})$ is a maximum of the firm's decision Problem (5.32).

We check the two conditions on the first derivative of $\hat{\Pi}(T)$ in turn. As for $\frac{\partial \hat{\Pi}}{\partial T}\mid_{T\to\tilde{T}^+}$, since T is approaching $\tilde{T}$ from above, after substituting

[17] We omit to state and prove Proposition 5.1 for the Cobb-Douglas case, as it is an obvious extension of the general case proved in Section 5.4.

[18] Notice that $\hat{T}>0$ requires $2\beta\gamma-\alpha>0$, which is satisfied whenever Assumption 4.7 holds. Moreover, in order to have $\hat{T}>\tilde{T}$, the following condition must be satisfied:

$$2\beta\gamma-\alpha<\frac{c}{1-c}.$$

One can immediately check that the latter is also a necessary and sufficient condition for $\left.\frac{\partial \hat{\Pi}}{\partial T}\right|_{T\to\tilde{T}^+}>0$. That $\hat{T}$ is a global maximum of the firm's problem in technology follows from the same arguments developed in Section 4.5.2 of Chapter 4.

(5.34) into (5.35) — where we made use of the envelope theorem — and evaluating it at $T \to \tilde{T}$, where $\tilde{T}$ is given in Equation (5.33), it is (after some algebra)

$$\frac{\partial \hat{\Pi}(T)}{\partial T} |_{T \to \tilde{T}^{+}} = \left(\hat{N} \left(\tilde{T} \right) \right)^{\beta} \tilde{T}^{\alpha - 1} \left[\alpha - 2\beta\gamma (1 - c) \right]. \tag{5.37}$$

The term in square brackets is positive if and only if $\alpha > 2\beta\gamma (1 - c)$. Since under Assumptions 4.5 and 4.7 it is $\alpha < \beta\gamma$, we can immediately conclude that a necessary, but not sufficient, condition for the above inequality to hold is $c > \frac{1}{2}$. For a spillover regime to emerge in this Cobb-Douglas economy, it is therefore necessary for the firm to have a good monitoring technology. In particular, *coeteris paribus*, the higher the probability to catch a shirker, the more likely the emergence of a spillover regime. Obviously, since $\alpha > 0$, the above condition is satisfied in the special case in which the firm has a perfect monitoring ability, i.e. $c = 1$, that is therefore a necessary and sufficient condition, even though a restrictive one.

As for $\frac{\partial \hat{\Pi}}{\partial T} |_{T = T_{\max}}$, again by substituting (5.34-b) into (5.35-b) and after some algebra, we get

$$\frac{\partial \hat{\Pi}}{\partial T} |_{T = T_{\max}} = \left(\hat{N} (T_{\max}) \right)^{\beta} T_{\max}^{\alpha - 1} \left[\alpha - \beta\gamma \frac{T_{\max}^{2\gamma}}{T_{\max}^{2\gamma}/2 + e} \right]. \tag{5.38}$$

It is immediate to see that $\frac{\partial \hat{\Pi}}{\partial T} |_{T = T_{\max}} < 0$ if and only if $\left[\alpha - \beta\gamma \frac{1}{1/2 + e/T_{\max}^{2\gamma}} \right] < 0$. Since $\gamma > 1$, for $e > 0$ and finite, a necessary and sufficient condition for this inequality to hold requires $T_{\max} \to +\infty$. However, this is obviously a more restrictive condition than needed. One can notice, for instance, that since $\beta\gamma > \alpha$ by Assumption 4.7, a sufficient condition for it to be negative is that

$$e < \frac{1}{2} T_{\max}^{2\gamma}. \tag{5.39}$$

As already noticed in the general framework discussed in the previous sections, Condition (5.39) highlights that it is the interplay between the parameter values for $T_{\max}$, γ and e to be responsible for the possible emergence of a spillover regime. The following example illustrates the point and derives a spillover equilibrium for a specific parameter set.

Example 5.1 *Consider a situation in which the firm has a decreasing returns to scale production function, and the self-employed production function is convex in the technology adopted by the firm. More precisely, assume the following parameter set:* $c = 1/4$, $e = 3$, $\alpha = 1/4$, $\beta = 1/2$, $\gamma = 2$, *and* $T_{\max} > \sqrt[4]{3/7}$. *It is immediate to check that Assumptions 4.5 - 4.7 are satisfied for the above parameter values. Plain algebra allows as well to check that these values guarantee that* $\frac{\partial \hat{\Pi}}{\partial T} |_{T \to \tilde{T}^+} > 0$ *and* $\frac{\partial \hat{\Pi}}{\partial T} |_{T = T_{\max}} < 0$, *where the two derivatives are computed in Equations (5.37) and (5.38) respectively. Notice finally that, for all* $\sqrt[4]{3/7} < T_{\max} \leq \sqrt[4]{6}$, *the derivative in Equation (5.38) is negative even though the sufficient condition (5.39) is not satisfied.*

In the framework developed in this dissertation, having assumed $T_{\max}$ and γ as exogenously given parameters seems rather innocuous. It is often assumed that the arrival rate of new technologies is exogenous. Moreover, as discussed in Chapter 2, there is a large literature investigating the innovation processes that has developed several mechanisms explaining the arrival rates of new technologies. Hence, the factors affecting the technology frontier $T_{\max}$ are well debated and understood. As for γ, it captures the entity of the production externalities induced by the firm's technology choice and it is therefore natural to treat it as a parameter.

We need, nevertheless, to be more cautious in treating the level of effort exerted by workers. Throughout the entire dissertation and in this Cobb-Douglas application as well, we have considered it as an exogenous parameter to keep our framework simple. In general however — as already stressed in Chapter 4 (Section 4.2) — it is reasonable to assume that e is a variable under the firm's control (at least up to a certain extent, and if it is possible to write appropriate incentive-compatible contracts as in our efficiency wage setup). Thus, it is reasonable to claim that it is related in specific ways to the technology adopted by the firm, i.e. it is a function $e(T)$ of the technology. Under the assumption that the firm is aware of the specific form of $e(T)$, this implies that it should take it into account in its decision problem, by considering explicitly the impact that the adoption of a certain technology has on the effort workers are required to exert. This, in turn, would affect the type of equilibrium that emerges, without however implying that some of the three possible regimes become unfeasible.

5.5.3 Comparative statics

We first look at the factors affecting the threshold at which production externalities start distorting the firm's decisions. As it has been for the general case discussed in the previous sections, and obviously for the same reasons, it is immediate to conclude that for the Cobb-Douglas economy we are studying a rise in the level of effort exerted by workers implies an increase of the technology grade at which externalities become relevant. In the same way, a sharpening of the firm's monitoring (as captured by an increase in the probability, c, of catching a shirker) determines a decrease in the threshold technology level $\tilde{T}$. Analytically, both findings follow immediately, by differentiating Equation (5.33) with respect to e and c respectively, i.e.

$$\frac{\partial \tilde{T}}{\partial e} = \frac{1-c}{c\gamma}\left(\frac{2e\,(1-c)}{c}\right)^{\frac{1-2\gamma}{2\gamma}} > 0, \qquad \frac{\partial \tilde{T}}{\partial c} = -\frac{e}{\gamma c^2}\left(\frac{2e\,(1-c)}{c}\right)^{\frac{1-2\gamma}{2\gamma}} < 0.$$

In order to assess the impact of a change in the level of effort on the firm's labor demand, when the blocked technology adoption regime applies (i.e. $T^* = \tilde{T}$), we substitute for $\tilde{T}$ into Equation (5.34). By differentiating with respect to e, after some algebra, we get

$$\frac{\partial \hat{N}\left(\tilde{T}\right)}{\partial e}=\frac{e\left(1-c\right)\left(\alpha-2\gamma\right)}{\beta\gamma c^{2}\left(1-\beta\right)}\left(\frac{e}{\beta c}\right)^{\frac{2-\beta}{\beta-1}}\left(\frac{2e\left(1-c\right)}{c}\right)^{\frac{\alpha-2\gamma(1-\beta)}{2\gamma(1-\beta)}}. \quad (5.40)$$

Since $0<(c,\beta)<1$ and $\alpha<2\gamma$ by Assumption 4.7, it is immediate to notice that the first term in Equation (5.40) is negative, while the other two are positive. Thus $\frac{\partial \hat{N}(\tilde{T})}{\partial e}<0$, meaning that an increase in the level of effort exerted by workers has a negative impact on equilibrium employment. This is a result following directly from the structure of the efficiency wage framework. As is standard in the efficiency wage literature, an higher disutility of effort requires the firm to pay an higher wage (at the equilibrium) in order to meet workers' incentive compatibility and individual rationality constraints. A higher wage, in turn, implies a lower labor demand by the firm.

We turn now to the impact of effort on the firm's technology choice when the spillover regime applies (i.e. $T^{*}=\hat{T}\in(\tilde{T},T_{\max})$). By differentiating Equation (5.36), we get

$$\frac{\partial \hat{T}}{\partial e}=\frac{\alpha}{\gamma\left(2\beta\gamma-\alpha\right)}\left(\frac{2\alpha e}{2\beta\gamma-\alpha}\right)^{\frac{1}{2\gamma}-1}, \quad (5.41)$$

that is greater than 0 under Assumptions 4.5 and 4.7. An increase in the workers effort determines an upward movement on the wage paid by the firm (i.e. $w^{*}=\frac{T^{*2\gamma}}{2}+e$). This, in turn, is responsible for reducing the impact of the adoption of a superior technology on wages, determining an improvement of the technology grade chosen in equilibrium. By inspection of (5.36) it is apparent that, for the Cobb-Douglas economy we are examining, the firm's monitoring has no impact on the technology it chooses in the spillover regime. As for the impact of effort on the equilibrium level of employment, by substituting for (5.36) and differentiating the relevant part of (5.34), after some algebra, it is

$$\frac{\partial \hat{N}\left(\hat{T}\right)}{\partial e} = \frac{1}{\beta-1}\left(\frac{\frac{e}{2\beta\gamma-\alpha}+e}{\beta\left(\frac{2e}{2\beta\gamma-\alpha}\right)^{\frac{\alpha}{2\gamma}}}\right)^{\frac{2-\beta}{\beta-1}} \cdot \qquad (5.42)$$

$$\left[e\beta^{-1}\left(\frac{2\beta\gamma-\alpha+1}{2\beta\gamma-\alpha}\right)\left(\frac{2e}{2\beta\gamma-\alpha}\right)^{-\frac{2\gamma+\alpha}{2\gamma}}\left(\frac{2\gamma-\alpha}{\gamma\left(2\beta\gamma-\alpha\right)}\right)\right].$$

It is easy to see that the term in square brackets in Equation (5.42) is greater than 0 by Assumptions 4.6 and 4.7, and since the first term is negative (by Assumption 4.6), an increase in the disutility of effort has a negative impact on equilibrium employment.

As for the impact on T and N of parameters α, β and γ, complexities and cross-effects are similar to those already analyzed for the Cobb-Douglas partial equilibrium economy, and discussed in Section 4.5.4 of Chapter 4.

5.6 Summary of Results

This chapter investigated technology adoption in a general equilibrium version of the economy introduced in Chapter 4. From a modeling point of view, the main contribution of the chapter consists in making explicit the link between the workers' outside options and the technology adopted by the firm, in the form of a technology-induced production externality from the market sector to the self-employment sector.

The market sector firm, in choosing a technology, can either take into account the impact of the externality on the entrepreneurs' productivity in the self-employment sector of the economy (the von Stackelberg case), or neglect it, treating the self-employed entrepreneurs' productivity as an exogenous parameter (the Cournot-Nash case). As it is to be expected, we have shown that in the latter case the presence of the technology-induced externality does not affect the market sector firm behavior. Since the firm fails to internalize the impact of the externality, and being profits increasing in technology, it always chooses the highest technology available. Hence, there is no technology misallocation and the Cournot-Nash equilibrium gives rise to the same equilibrium that would be observed in a perfectly competitive environment.

The situation changes when the firm behaves in a more sophisticated manner (i.e. as a von Stackelberg leader in our terminology) by internalizing the externality. In this case, on the one hand, the adoption of a superior technology increases the productivity of the firm's employees and, thus, its profits. On the other hand, it provokes an increase in the firm's labor costs, needed to compensate for the better outside options (i.e. the increase in productivity under self-employment stemming from the production externality) available to its employees experienced with the new technology. In other words, whenever the firm knows and takes explicitly into account the link between the technology it operates and the productivity in the self-employment sector, the presence of the externality renders workers' participation (or individual rationality) constraint endogenous in the firm's choice of technology. As a consequence, the adoption of a superior technology may determine an increase in the wage sufficient to induce the firm not to adopt it in the first place. The two sources of non-marketed relations described — i.e. the positive externality on the production function of the self-employed entrepreneurs and the negative pecuniary externality represented by the increase in labor costs for the market sector firm — are thus responsible for the possibility of technology misallocation in the von Stackelberg regime.

Note, finally, that the economy presented in this chapter shares in many respects the same underlying structure as the economy studied in the partial equilibrium setting of Chapter 4. Therefore, it suffers from many of the same structural limits and leaves room for the same extensions outlined there (see Section 4.6). One further extension not mentioned there, and in principle relevant in a general equilibrium framework accounting for all feedback effects in the economy, concerns the links between the *disutility of effort*, the *cost of skills acquisition* and the technology adopted by the market sector firm (briefly discussed at the end of Section 5.5.2 in the framework of the Cobb-Douglas example). One might in fact argue that the technologies chosen by firms have an impact both on workers' (disutility of) effort and on the cost to acquire further skills. As far as the adoption of a superior technology reduces the disutility of effort or the costs of skill acquisition, it reduces the incentive of a worker to shirk, and at the same time it is likely to increase the size of the externality a self-employed entrepreneur can benefit from. This in turn has an impact on the firm's wage offers and, ultimately, on the possibility of technology misallocation.

6

Market Failure and Policy Analysis

6.1 Introduction

When the market sector firm behaves like a von Stackelberg leader, the general equilibrium economy studied in Chapter 5 presents two sources of externality that are likely to produce inefficiencies of market allocations. On the one hand, technology adoption by the firm exerts a positive externality on the production function of self employed workers. On the other hand, this positive externality generates a negative pecuniary externality on the firm, determined by increasing labor costs for all technologies above a certain threshold level (due to spillover effects). This double source of non-marketed relations may dampen technology adoption by the firm and may also affect the labor distribution across sectors. It is, therefore, natural to ask whether there is a role for the government in trying to overcome the inefficiencies induced by the presence of externalities and to support Pareto efficient allocations.[1] Building on the framework developed in Chapter 5, this chapter focuses on the con-

[1] Various types of government intervention and their scopes have already been briefly discussed in Chapter 2.

sequences of the non-marketed relations discussed above and conduct a normative analysis of the welfare implications of the presence of externalities in the technology adoption process. We first characterize the Pareto efficient allocations that would be generated by a social planner internalizing all sources of externalities, and we compare them with the market allocations derived in Chapter 5.

We then examine whether government intervention is able to overcome market failure, in the simple framework in which the government's budget is assumed to balance, and all subsidies (taxes) are financed via a lump sum tax (subsidy) on consumers. We study various types of policy intervention schemes to overcome the possible inefficiencies in market allocations, ranging from non-linear (first best) subsidization mechanisms to second best — but eventually more realistic — policy instruments based on Pigouvian subsidies/taxes on labor input and/or technology adoption. In particular, we show that by implementing a (first best) non-linear subsidy, the government can overcome market failure by enforcing at no cost truthful revelation of the choice variables on which the transfer to the externality producer is contingent. We then take the informationally less demanding view that the government does not know the entire structure of the economy and we implement less sophisticated (in terms of the amount of information needed) policy instruments. In particular, we introduce fixed unity Pigouvian subsidies (taxes) on workers employed by the firm and/or on each unit of technology adopted and we show that subsidies on technology can always increase social welfare, while a welfare improving intervention on labor demand may require either a subsidy or a tax.

The chapter is organized as follows. Section 6.2 characterizes Pareto efficient allocations and compares them with market allocations, pausing as well on questions related to distribution and incentive compatibility. Section 6.3 deals with policy analysis focusing on non-linear first best subsidization, and on second best policy instruments in the form of Pigouvian subsidies on labor input and on technology adoption. Section 6.4 applies some of the analysis to the same Cobb-Douglas economy investigated in the previous chapters. Finally, Section 6.5 concludes.

6.2 Pareto efficient allocations

Throughout the chapter we deal with the same general equilibrium economy introduced in Chapter 5 and, hence, we maintain the same set of assumptions made there. In this framework, Pareto efficient allocations are characterized as follows. As a first step, we recognize that Pareto efficiency must be compatible with the resource constraint of the economy, in the obvious sense that aggregate consumption must not exceed aggregate output, that is:

$$\omega N + \omega_f N_f + \omega_u N_u \leq \Phi(N, T) + g(T) h_f N_f \tag{6.1}$$

where ω, ω_f and ω_u denote the total consumption of the agent working for the firm, the self-employed and the unemployed, respectively; N, N_f, N_u denote the number of workers employed by the firm, of self-employed and of unemployed respectively, with

$$N \geq 0, N_f \geq 0, \;\; N_u \geq 0, \;\text{ and } N + N_f + N_u = \bar{N}. \tag{6.2}$$

From (6.1), subtracting from both sides $eN + \varphi(h_f)N_f$ we obtain

$$\begin{aligned}(\omega - e)\, N + [\omega_f - \varphi(h_f)]N_f + \omega_u N_u \;\; &\leq \;\; \Phi(N, T) - eN + \\ &+ (g(T)h_f - \varphi(h_f))\, N_f\end{aligned} \tag{6.3}$$

The left hand side of (6.3) is aggregate social welfare (according to a utilitarian social welfare function), whereas the right hand side is aggregate production net of aggregate social cost, represented by labor effort disutility which is expressed, by assumption, in equivalent consumption units.

From a normative point of view, Pareto efficient allocations must be characterized by the absence of unemployment (i.e. $N_u = 0$), since the labor productivity of all agents in the economy is strictly greater than zero. Moreover, Pareto efficiency requires that there are no resources that remain unused in equilibrium. Hence the third constraint in Condition (6.2) must read $N + N_f = \bar{N}$. Turning to the optimal allocation problem, irrespective of distributional choices (i.e. the choice of total consumption levels), Pareto efficiency requires to maximize the right hand side of Inequality (6.3) with respect to T, N, h_f and N_f. In this respect, a first result is immediately apparent: since $\partial\Phi/\partial T > 0$ and $g' > 0$, the right hand side of (6.3) is strictly increasing in T for all (N, h_f, N_f) triples provided that at least N or N_f is non-zero (with also $h_f > 0$ in the latter case), and hence at the optimum $T = T_{\max}$. Also, for any given (T, N_f), h_f must be chosen so that $g(T)h_f - \varphi(h_f)$ is maximized, which gives $h_f(g)$ as a solution as in market equilibrium. Hence, at the social optimum, $T^{**} = T_{\max} \geq T^*$ and $h_f^{**} = h_f^*$. To distinguish Pareto efficient allocations from market allocations, the former are marked with a double asterisk.

Next we turn to the optimal allocation of labor. By maximizing the right hand side of (6.3) with respect to N at $T^{**} = T_{\max}$ and recalling that $N_f = \bar{N} - N$, it is

$$\frac{\partial\Phi(N, T_{\max})}{\partial N} - e - g(T_{\max})h_f^{**} + \varphi(h_f^{**}) = 0. \tag{6.4}$$

Let $\breve{N}$ be the value of N that solves (6.4). Given Assumption 5.4, $\breve{N}$ is positive and unique; also, under Assumption 5.7, $\breve{N} < \bar{N}$, meaning that there will be self-employed entrepreneurs at the Pareto efficient equilibrium.

Notice that Condition (6.4) requires that the marginal return on labor is the same in the market sector and in the self-employment sector of the economy. In fact, by defining the aggregate net output in the right hand side of (6.3) as Y, we get

$$\left.\frac{\partial Y}{\partial N}\right|_{T=T_{\max}} \equiv \frac{\partial \Phi(N, T_{\max})}{\partial N} - e = g(T_{\max})h_f^{**} - \varphi(h_f^{**}) \equiv \left.\frac{\partial Y}{\partial N_f}\right|_{T=T_{\max}}. \tag{6.5}$$

We can summarize the previous discussion by characterizing Pareto efficient allocations through the following proposition:

Proposition 6.1 *Given parameters e and $T_{\max}$, Pareto efficient allocations are as follows: $T^{**} = T_{\max}$, $g^{**} = g(T^{**})$, $h_f^{**} = h_f^*$, $N^{**} = \breve{N}$, $N_f^{**} = \bar{N} - \breve{N}$, $N_u^{**} = 0$.*

In order to compare market allocations with Pareto allocations, we prove the following proposition.

Proposition 6.2 *When $T^* < T_{\max}$ there is technology misallocation but not labor misallocation. When $T^* = T^C = T_{\max}$ there are neither technology nor labor misallocation.*

Proof. When $T^* < T_{\max}$ we only need to prove that there is no labor misallocation. We know, by Proposition 5.1, that in a market equilibrium it must be $T^* \geq \tilde{T}$. Therefore, by Equation (5.18) it is $W(g(T^*)) = g(T^*)h_f^* - \varphi(h_f^*) + e$. By substituting this expression for $W(g(T^*))$ into Equation (5.22), it is immediate to check that it reads exactly as Equation (6.5), which proves the claim.

Also when $T^* = T_{\max}$ we only need to prove that there is no labor misallocation. This follows directly by the comparison of Equations (5.22) and (6.5) using Condition (5.18). ■

Given Proposition 6.2, policy intervention is called for only when $T^* < T_{\max}$. In other words, it turns out to be useful only in the von Stackelberg case, while in the Cournot case market and Pareto allocations coincide.

Before turning to policy analysis, we note that, having determined the allocations of inputs that maximize total output, the social planner can move on focusing on distributional issues and on incentive compatibility.

In our framework, these objectives are achieved by choosing the ω's under the constraint of Pareto efficiency. Formally, this requires the planner to choose ω and ω_f under the constraints $\omega - e \geq 0$, $\omega_f - \varphi(h_f^{**}) \geq 0$ and

$$(\omega - e)\, N^{**} + [\omega_f - \varphi(h_f^{**})] N_f^{**} \leq Y^{**}, \tag{6.6}$$

where $Y^{**} = \Phi(N^{**}, T_{\max}) - eN^{**} + g(T_{\max}) h_f^{**} N_f^{**} - \varphi(h_f^{**}) N_f^{**}$.

Due to the focus on technology adoption problems, however, our modelling of the economy abstracts from many important issues that should, instead, be considered when dealing with income distribution (thus rendering the study of problems like the one outlined by the inequality in (6.6) a special case and a quite limited one in terms of economic insights). Hence, we do not further pursue these topics, turning instead to policy analysis.

6.3 Policy analysis

We now examine how government intervention is able to overcome (or at least mitigate) market failure offsetting the production externality that is not internalized by the firm, by considering various types of subsidization policies.

6.3.1 Non-linear (first best) subsidization

It is a matter of algebra to show that the government can achieve a Pareto efficient outcome by introducing non-linear subsidies. Suppose the government grants the firm a subsidy S for each employee, which is conditional on the level of technology adoption and on the level of employment, of the form

$$S(T,N) := \begin{cases} \begin{array}{l} e/c - e + [g(T_{\max}) h_f\left(g\left(T\right)\right) + \\ -\varphi(h_f\left(g\left(T\right)\right))] \frac{\bar{N}-N}{N}, \end{array} & T \in [0, \tilde{T}) \\ \begin{array}{l} g(T) h_f\left(g\left(T\right)\right) - \varphi(h_f\left(g\left(T\right)\right)) + \\ \left[g(T_{\max}) h_f\left(g\left(T\right)\right) - \varphi(h_f\left(g\left(T\right)\right))\right] \frac{\bar{N}-N}{N}, \end{array} & T \in [\tilde{T}, T_{\max}] \end{cases} . \tag{6.7}$$

The policy maker is assumed to move first by setting tax policy, and then producers make their choices as described in Section 5.2.2. Government's budget is assumed to balance; in particular any subsidy (tax) paid (levied) to producers is financed with a lump sum tax (subsidy) on consumers. The use of a lump sum tax is without loss of generality, as other non-distortive tax instruments are available within this framework. For instance, a proportional tax on the firm's gross profits or on consumers' dividends does not affect the choices made by the firm, by the self-employed workers and by consumers, and hence is equivalent to a lump sum tax on consumers.

Under the subsidy defined in Equation (6.7), the firm's profit function becomes

$$\Pi = \Phi(N,T) - (W(g(T)) - S(T,N))N$$

where $W(g(T))$ is defined as in (5.18). Since we have assumed away income effects, the lump sum tax on consumers does not affect the participation and incentive compatibility constraints. Hence, by Equations (5.18) and (6.7), and after some algebra, we have

$$W(g(T)) - S(T,N) = e + [\varphi(h_f(g(T))) - g(T_{\max})h_f(g(T))]\frac{\bar{N}-N}{N}$$

for all T, and thus the problem of the firm reduces to

$$\max_{T,N} \quad \Pi = \Phi(N,T) - eN + [g(T_{\max})h_f(g(T)) - \varphi(h_f(g(T)))]\left(\bar{N}-N\right). \tag{6.8}$$

The solution of Problem (6.8) gives $T = T_{\max}$ and a first order condition for the choice of N that, once evaluated at $T = T_{\max}$, is identical to (6.5) characterizing Pareto efficient allocations. This follows immediately from the observation that, by differentiating Π with respect to T (recalling that $\partial\varphi(.)/\partial h_f(.) = g(T)$), it is

$$\frac{\partial\Pi}{\partial T} = \frac{\partial\Phi(N,T)}{\partial T} + \frac{dh_f(g(T))}{dg}\frac{dg(T)}{dT}[g(T_{\max}) - g(T)]\left(\bar{N}-N\right) > 0,$$

and, moreover, that the first order conditions of Problem 6.8 with respect to N is given by

$$\frac{\partial \Pi}{\partial N} = \frac{\partial \Phi \left(N, T\right)}{\partial N} - e - g(T_{\max})h_f\left(g\left(T\right)\right) + \varphi(h_f\left(g\left(T\right)\right)) = 0.$$

Hence, with the non-linear subsidy (6.7), the decentralized market equilibrium achieves a Pareto efficient allocation. Policy intervention corrects for market failure and achieves a first best allocation. Indeed, the externality producer is induced to maximize aggregate net output as in the social planner problem, since the objective function in (6.8) is identical to the right hand side of (6.3).

The above discussion is summarized in the following proposition:

Proposition 6.3 *Policy subsidization through the non-linear subsidies* $S\left(T, N\right)$ *— defined in Equation (6.7) — corrects for market failure allowing the economy to achieve the Pareto efficient equilibrium defined in Proposition 6.1.*

Figure 6.1 shows how the introduction of a non-linear subsidy per employee leads to Pareto efficiency. Both graphs in the figure show that the introduction of the subsidy S (Equation 6.7) affects the constraint on wages faced by the firm (Equation 5.18) shifting it downward to the point at which the optimal technology choice by the firm becomes $T_{\max}$.[2]

To implement the non-linear subsidy, the policy maker needs, however, to have a great deal of information; indeed it needs to know the entire structure of the economy, as is standard in optimal policy analysis. The point is that it observes and can enforce truthful revealing at no cost (i.e costless monitoring) of both N and T, which are the choice variables on which the transfer to the firm is contingent. These information requirements are in many cases so demanding that the actual implementability

[2] Section 6.4 illustrates the impact of non-linear first best subsidization for the Cobb-Douglas economy introduced in Chapter 5.

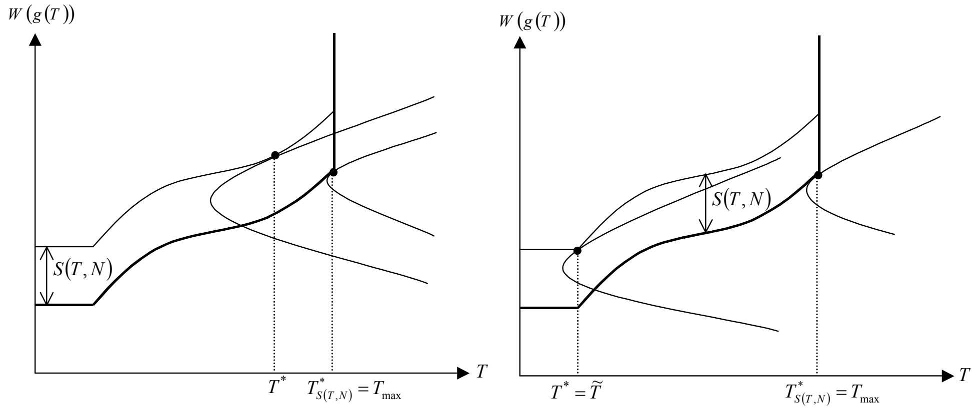

FIGURE 6.1. Non-linear (first best) subsidization

of such first best policy instruments is greatly reduced if not impaired, which suggests to look at instruments imposing a smaller informational burden on the policy maker.

6.3.2 Second best policy instruments

We now consider two less sophisticated, but more realistic, policy instruments affecting the marginal returns to work and technology. The first one is a fixed unit subsidy, at rate s, on workers employed by the externality producer; the second one is a fixed unit subsidy, at rate σ, on each unit of technological adoption. Both s and σ are simple to implement, since it is reasonable to assume that both the employment level and the type of technology adopted are observed. Also, these kind of instruments are widely employed in real tax systems: s can be assimilated to a (negative) payroll tax, whereas σ resembles the kind of incentive schemes that governments grant to induce firms to dismiss old equipments for new ones.[3] Moreover, the introduction of second best policy instruments is needed

[3] A third tax instrument that can be used to indirectly affect the firm choices is a tax or subsidy on self-employed workers' labor input. It is immediate to show that this is equivalent to the subsidy s on the firm labor inputs.

whenever there is imperfect observability (or possibility of cheating on) of T.

As a first step in addressing the effects of second best policy measures, we start focusing on the problem faced by the firm, that becomes

$$\max_{N,T} \quad \Pi = \Phi(N,T) + \sigma T - (W(g(T)) - s)N, \tag{6.9}$$

where $W(g(T))$ is defined as in (5.18).

Consider first the choice of labor input, given T. The first order condition for an interior solution is

$$\frac{\partial \Pi}{\partial N} = \frac{\partial \Phi(N,T)}{\partial N} - W(g(T)) + s = 0, \tag{6.10}$$

which gives $\hat{N}(T, W(g(T)), s)$ as a solution. Clearly,

$$\partial \hat{N}/\partial s = -\left(\partial^2 \Phi/\partial N^2\right)^{-1} > 0,$$

so that labor demand is independent of σ.

Substituting $\hat{N}$, $\hat{N} \equiv \hat{N}(T, W(g(T)), s)$, into the profit function (6.9), the problem of technological adoption can now be written as

$$\max_{T} \quad \hat{\Pi} = \Phi(\hat{N},T) + \sigma T - (W(g(T)) - s)\hat{N}.$$

Thus, given $\hat{N}$, the first order condition for an interior solution is

$$\frac{\partial \hat{\Pi}}{\partial T} = \frac{\partial \Phi(\hat{N},T)}{\partial T} + \sigma - \hat{N}\frac{dW(g(T))}{dT} = 0. \tag{6.11}$$

Let the solution be $T(s,\sigma)$. By totally differentiating (6.11) with respect to s — and recalling that $\hat{N}$ is a function of s — we get

$$\frac{\partial^2 \hat{\Pi}}{\partial T^2}\frac{dT}{ds} + \frac{\partial^2 \Phi(\hat{N},T)}{\partial T \partial N}\frac{\partial \hat{N}}{\partial s} - \frac{\partial \hat{N}}{\partial s}\frac{dW(g(T))}{dT} = 0. \tag{6.12}$$

From Equation (5.23) it is

$$\frac{dW(g(T))}{dT} = \frac{\partial \hat{N}}{\partial T}\frac{\partial^2 \Phi(\hat{N},T)}{\partial N^2} + \frac{\partial^2 \Phi(\hat{N},T)}{\partial T \partial N},$$

and substituting into (6.12), we get

$$\frac{dT}{ds} = \frac{\partial^2 \Phi}{\partial N^2} \frac{\partial \hat{N}}{\partial T} \frac{\partial \hat{N}}{\partial s} \Bigg/ \frac{\partial^2 \hat{\Pi}}{\partial T^2} \tag{6.13}$$

Finally, by differentiating (6.11) with respect to σ, we obtain

$$\frac{dT}{d\sigma} = -\left(\frac{\partial^2 \hat{\Pi}}{\partial T^2}\right)^{-1} \tag{6.14}$$

where, again by making use of (5.23), it is[4]

$$\frac{\partial^2 \hat{\Pi}}{\partial T^2} = \frac{\partial^2 \Phi}{\partial T^2} - \frac{\partial^2 \Phi}{\partial N^2}\left(\frac{\partial \hat{N}}{\partial T}\right)^2 - \hat{N}\frac{\partial^2 W\left(g\left(T\right)\right)}{\partial T^2}. \tag{6.15}$$

By inspection of Equations (6.13) and (6.14), it is immediate to notice that the signs of $\frac{dT}{ds}$ and $\frac{dT}{d\sigma}$ are undecided, depending on the sign of $\frac{\partial^2 \hat{\Pi}}{\partial T^2}$ that remains an empirical matter.

As for policy analysis, let us now consider each tax instrument in turn.

Pigouvian subsidy on labor input

Let $\sigma = 0$. We wish to analyze whether social welfare can be increased by using the subsidy on labor input, s, while balancing the budget with the lump sum tax, Θ, that has no influence on work incentives because of the linearity assumption. Assuming a utilitarian social welfare functional, the policy maker solves the following problem

$$\max_{s,\Theta} \quad \mathcal{V} = V^{ns*}N^* + V_f^* N_f^* \tag{6.16}$$

$$\text{s.t.} \quad sN^* = \Theta \bar{N}.$$

Since, in a market equilibrium, $N_f^* = \bar{N} - N^*$ and $V^{ns*} = V_f^*$, the social welfare function can be written as

$$\begin{aligned}\mathcal{V} \;&=\; \left(w_f^* - \varphi(h_f^*\left(g\left(T^*\right)\right)) + \frac{\Pi^*}{\bar{N}} - \Theta\right)\bar{N} = \\ &\quad [g(T^*)h_f^*\left(g\left(T^*\right)\right) - \varphi(h_f^*\left(g\left(T^*\right)\right))]\bar{N} + \Pi^* - \Theta\bar{N}. \end{aligned} \tag{6.17}$$

[4] The following equation is the same as Equation (5.26), but (6.15) is defined for all T whereas (5.26) only for $T > \tilde{T}$.

Substituting in (6.17) the budget constraint, we can finally write the optimal tax Problem (6.16) as

$$\max_{s} \mathcal{V} = [g(T^*(s))h_f^*(g(T^*(s))) - \varphi(h_f^*(g(T^*(s))))]\bar{N} + \Pi^*(s) - sN^*(s). \tag{6.18}$$

Differentiating $\mathcal{V}$ with respect to s, the first order condition of Problem (6.18) is

$$\begin{aligned} \frac{d\mathcal{V}}{ds} &= [h_f^*(g(T^*(s)))\frac{\partial g(T^*(s))}{\partial T}\frac{\partial T^*(s)}{\partial s} + \\ &+ g(T^*(s))\frac{\partial h_f^*(g(T^*(s)))}{\partial g}\frac{\partial g(T^*(s))}{\partial T}\frac{\partial T^*(s)}{\partial s} + \\ &- \frac{\partial \varphi(h_f^*(g(T^*(s))))}{\partial h_f}\frac{\partial h_f^*(g(T^*(s)))}{\partial g}\frac{\partial g(T^*(s))}{\partial T}\frac{\partial T^*(s)}{\partial s}]\bar{N} + \\ &+ \frac{\partial \Pi^*(s)}{\partial s} - N^*(s) - s\frac{\partial N^*(s)}{\partial s} = 0 \end{aligned}$$

which can be rewritten as

$$\begin{aligned} &\left\{h_f^*(g(T^*(s)))\frac{\partial g(T^*(s))}{\partial T}\frac{\partial T^*(s)}{\partial s} + \right. \\ &\left.\left[g(T^*(s)) - \frac{\partial \varphi(h_f^*(g(T^*(s))))}{\partial h_f}\right]\frac{\partial h_f^*(g(T^*(s)))}{\partial g}\frac{\partial g(T^*(s))}{\partial T}\frac{\partial T^*(s)}{\partial s}\right\}\bar{N} + \\ &+ \frac{\partial \Pi^*(s)}{\partial s} - N^*(s) - s\frac{\partial N^*(s)}{\partial s} = 0. \end{aligned} \tag{6.19}$$

By the envelope theorem it is $\frac{\partial \Pi^*(s)}{\partial s} = N^*(s)$, and by the first order condition of the self-employed workers' utility maximization problem (i.e. Problem (5.8)) it is $g(T^*(s)) = \frac{\partial \varphi(h_f^*(g(T^*(s))))}{\partial h_f}$. Thus Equation (6.19) reduces to

$$h_f^*(g(T^*(s)))\frac{\partial g(T^*(s))}{\partial T}\frac{\partial T^*(s)}{\partial s}\bar{N} - s\frac{\partial N^*(s)}{\partial s} = 0.$$

Therefore, if an interior solution exists, s is defined implicitly by

$$s = \frac{\bar{N}h_f^*(g(T^*(s)))\frac{\partial g(T^*(s))}{\partial T}\frac{\partial T^*(s)}{\partial s}}{\frac{\partial N^*(s)}{\partial s}}. \tag{6.20}$$

The optimal s can be both negative or positive, meaning that social welfare can be increased by using either a fixed unity subsidy or tax on labor input depending on whether it is a subsidy ($s > 0$) or a tax ($s < 0$) that induces higher technology adoption than in the *laissez faire* equilibrium. This matter can not be solved analytically. In fact, s is greater or smaller than zero depending on the sign of $\partial T^*/\partial s$ at the numerator of Equation (6.20). The sign of $\partial T^*/\partial s$, defined by Equation (6.13), depends in turn on the sign of $\frac{\partial \hat{N}}{\partial T}$ and $\frac{\partial^2 \hat{\Pi}}{\partial T^2}$. While, as noticed by discussing Equation (5.23), it is easy to characterize the sign of $\frac{\partial \hat{N}}{\partial T}$, it is not possible to provide general conditions for the sign of $\frac{\partial^2 \hat{\Pi}}{\partial T^2}$ which remains an empirical matter, as emphasized when studying Equation (5.26).

The above discussion is summarized, slightly abusing notation, in the following proposition.

Proposition 6.4 *If there exists an interior optimal s^*, then s^* satisfies the necessary condition*

$$s^* = \frac{g' h_f^* \bar{N} (\partial T^*/\partial s)}{\partial N^*/\partial s}.$$

Therefore, s^* is negative (a tax) if $\partial T^*/\partial s$ and $\partial N^*/\partial s$ have opposite sign; otherwise it is positive (a subsidy).

Pigouvian subsidy on technology adoption

Let $s = 0$. The tax instrument used by the policy maker is now the fixed unit subsidy on technology σ. Using (6.17), and after substituting for the budget constraint $\sigma T = \Theta \bar{N}$, the optimal tax problem is

$$\max_{\sigma} \mathcal{V} = [g(T^*(\sigma)) h_f^* (g(T^*(\sigma))) - \varphi(h_f^* (g(T^*(\sigma))))] \bar{N} + \Pi^*(\sigma) - \sigma T^*(\sigma). \tag{6.21}$$

The first order condition of Problem (6.21) can be written as

$$\frac{d\mathcal{V}}{d\sigma}=[\frac{\partial g\left(T^{*}\left(\sigma\right)\right)}{\partial T}\frac{\partial T^{*}\left(\sigma\right)}{\partial\sigma}h_{f}^{*}\left(g\left(T^{*}\left(\sigma\right)\right)\right)+$$
$$+g(T^{*}\left(\sigma\right))\frac{\partial h_{f}^{*}\left(g\left(T^{*}\left(\sigma\right)\right)\right)}{\partial g}\frac{\partial g\left(T^{*}\left(\sigma\right)\right)}{\partial T}\frac{\partial T^{*}\left(\sigma\right)}{\partial\sigma}+$$
$$-\frac{\partial\varphi(h_{f}^{*}\left(g\left(T^{*}\left(\sigma\right)\right)\right))}{\partial T}\frac{\partial h_{f}^{*}\left(g\left(T^{*}\left(\sigma\right)\right)\right)}{\partial g\left(T^{*}\right)}\frac{\partial g\left(T^{*}\left(\sigma\right)\right)}{\partial T}\frac{\partial T^{*}\left(\sigma\right)}{\partial\sigma}]\bar{N}+$$
$$+\frac{\partial\Pi^{*}\left(\sigma\right)}{\partial\sigma}-T^{*}\left(\sigma\right)-\sigma\frac{\partial T^{*}\left(\sigma\right)}{\partial\sigma}=0.$$

Recalling that $\frac{\partial g(T^{*}(\sigma))}{\partial T}=\frac{\partial\varphi(h_{f}^{*}(g(T^{*}(\sigma))))}{\partial T}$, we get

$$\frac{\partial g\left(T^{*}\left(\sigma\right)\right)}{\partial T}\frac{\partial T^{*}\left(\sigma\right)}{\partial\sigma}h_{f}^{*}\left(g\left(T^{*}\left(\sigma\right)\right)\right)\bar{N}+\frac{\partial\Pi^{*}\left(\sigma\right)}{\partial\sigma}-T^{*}\left(\sigma\right)-\sigma\frac{\partial T^{*}\left(\sigma\right)}{\partial\sigma}=0. \tag{6.22}$$

Since by using the envelope theorem it is $\frac{\partial\Pi(\sigma)}{\partial\sigma}=T\left(\sigma\right)$, we obtain the following implicit equation for σ

$$\sigma=\frac{\partial g\left(T^{*}\left(\sigma\right)\right)}{\partial T}h_{f}^{*}\left(g\left(T^{*}\left(\sigma\right)\right)\right)\bar{N}>0, \tag{6.23}$$

which shows that a Pigouvian subsidy unambiguously gives the proper incentive to foster technology adoption. In this sense, it is better than a Pigouvian subsidy on labor input since it gives rise unambiguously to a welfare improvement. Moreover, being levied on the variable that the policy maker needs to affect (i.e. T), it is more direct than a fixed unity subsidy (or tax) on labor input that acts only indirectly through N^{*}. Figure 6.2 illustrates how a subsidy σ on technology adoption affects the technology chosen by the firm, and Proposition 6.5 summarizes the above arguments.

Proposition 6.5 *A Pigouvian subsidy on technology, σ^{*}, defined implicitly by Condition (6.23), always fosters technology adoption. Differently from a Pigouvian subsidy on labor input, it gives rise unambiguously to a welfare improvement.*

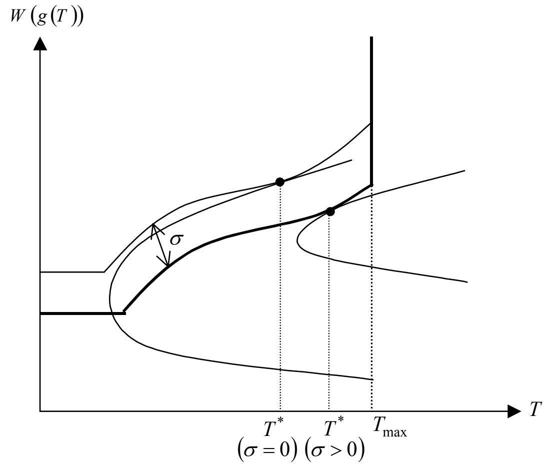

FIGURE 6.2. A second best subsidy on technology

6.4 An example: Cobb-Douglas economy

In this section, we discuss welfare analysis for the same Cobb-Douglas economy considered in the previous chapters, by briefly focusing on Pareto efficiency and on policy intervention, for the latter investigating non-linear first best subsidies only.[5]

All assumptions made in Section 4.5 of Chapter 4 and in Section 5.5 of Chapter 5 continue to hold here too. In order to determine Pareto efficient allocations, we need to maximize aggregate production net of aggregate social costs, as defined by the right hand side of Inequality (6.3), that for the Cobb Douglas economy under scrutiny specializes into:

$$\max_{T,N,h_f,N_f} \quad Y(T,N,h_f,N_f) := T^{\alpha}N^{\beta} - eN + \left(T^{\gamma}h_f - h_f^2/2\right)N_f \quad (6.24)$$

By mimicking the same arguments developed in the previous sections for the general case, it is immediate to notice that Y is strictly increasing in T, for all (N,h_f,N_f) triples, provided N or (h_f,N_f) are different from

[5] The study of second best policy measures proves to be algebraically demanding under the Cobb-Douglas specification studied here. The problems at hand can be solved only for specific parameters configurations. A full characterization of parameter regions, however, does not add much in terms of economic insights, and thus we omit it.

zero. Thus $T^{**} = T^* = T_{\max}$. (Recall that we use a double asterisk to denote Pareto efficient allocations). Moreover, for any (T, N_f), h_f is chosen so as to maximize $T^\gamma h_f - h_f^2/2$, and thus $h_f^{**} = h_f^* = T_{\max}^\gamma$. As for the optimal labor allocation, it must be that the marginal return on labor is the same in the market sector and in the self-employment sector of the economy (see Equation (6.5)), and hence:

$$\beta T_{\max}^\alpha N^{\beta-1} - e = T_{\max}^{2\gamma} - \frac{T_{\max}^{2\gamma}}{2},$$

i.e.,

$$\beta T_{\max}^\alpha N^{\beta-1} = e + \frac{T_{\max}^{2\gamma}}{2}, \tag{6.25}$$

from which it follows

$$N^{**} = \breve{N} = \left(\frac{e + T_{\max}^{2\gamma}/2}{\beta T_{\max}^\alpha} \right)^{\frac{1}{\beta-1}}. \tag{6.26}$$

Policy intervention is called for whenever the market equilibrium is such that $T^* < T_{\max}$. This implies that there is a role for an active fiscal policy only under the von Stackelberg scenario. Indeed, it is immediate to notice that in the Cournot-Nash framework, market allocations and Pareto allocations coincide.[6]

As already stated above, we only consider the set of instruments proposed in Section 6.3.1 in order to overcome market failure: that is, *non-linear first best subsidies.*

By introducing a per-employee subsidy $S(T, N)$, the firm's profit function is

$$\Pi = T^\alpha N^\beta - (W(T) - S(T, N)) N,$$

[6] The technology adopted by the firm is $T_{\max}$ in both cases and, comparing Equations (6.26) and (5.30) where

$$W(G) = e + \frac{T_{\max}^{2\gamma}}{2},$$

by making use of Equation (6.25), it is immediate to note that also the employment level is the same.

where $W(T)$ is defined in Equation (5.31) and the subsidy $S(T,N)$ is equal to

$$S(T,N)=\begin{cases}\frac{e}{c}-e+\left(T_{\max}^{\gamma}T^{\gamma}-\frac{T^{2\gamma}}{2}\right)\frac{\bar{N}-N}{N} & T\in\left[0,\tilde{T}\right)\\ \left(T_{\max}^{\gamma}T^{\gamma}-\frac{T^{2\gamma}}{2}\right)\frac{\bar{N}-N}{N}+\frac{T^{2\gamma}}{2} & T\in\left[\tilde{T},T_{\max}\right]\end{cases}.$$

By substituting for $W(T)$ and $S(T,N)$, the firm's problem becomes

$$\max_{T,N}\quad T^{\alpha}N^{\beta}+\left(T_{\max}^{\gamma}-\frac{T^{\gamma}}{2}\right)T^{\gamma}\frac{\bar{N}-N}{N}-eN. \tag{6.27}$$

Since the above program is increasing in T, it is immediate to observe that, following the introduction of the non-linear subsidy, it is $T^{*}=T_{\max}$. Moreover, it is also straightforward to notice that at $T=T_{\max}$, Problem (6.27) gives a first order condition for the choice of employment identical to the condition characterizing the optimal (Pareto efficient) allocation of labor, i.e.

$$\beta T_{\max}^{\alpha}N^{\beta-1}=e+\frac{T_{\max}^{2\gamma}}{2}. \tag{6.28}$$

Hence, non-linear subsidization conditional on the level of technology and employment allows to eliminate the distortion in technology adoption without introducing any distortion in the allocation of labor.

6.5 Concluding remarks

The inefficiencies created by the presence of external effects set the stage for the consideration of government intervention. In this chapter we studied the market failures generated by the production and pecuniary externalities arising in the framework developed in Chapter 5, and discussed the problems they pose from a normative point of view, investigating the tools that can be used in order to improve social welfare. We first characterized the Pareto efficient allocations that are generated by a social planner internalizing all sources of externalities and compared them with the market allocations derived in Chapter 5, showing when technology misallocation is likely to be observed. Second, we investigated different government intervention policies that can mitigate or overcome market failure, starting with non-linear subsidization, that proves capable to achieve Pareto efficiency by rendering the adoption of an inefficient technology a dominated strategy. We then turned to second best policy instruments proving that Pigouvian subsidies on technology always help in increasing social welfare. Interventions on labor demand have instead an ambiguous impact on welfare, in the sense that, depending on the circumstances, either a fixed unity tax or a subsidy on labor input can induce higher technology adoption.

The way the government's activity is modeled remains very simple throughout the chapter. In the static setting we consider, all issues of commitment or time consistency of the government's actions possibly arising from the presence of production externalities are ruled away.[7] The budget is assumed to balance and all interventions are financed via a lump sum tax on consumers, or other equivalent non-distortive tax instruments. In a more complicated framework such non-distortive taxes may not be readily available and, in general, it is likely that taxes introduce distortions in agents' behavior. One would therefore have to face a trade-off between the costs deriving from the distortionary impact associated with the design of the tax system and the means it provides to correct the externalities. Whenever non-distortive taxes are not at hand, the design of the tax system becomes important to guarantee that no worse distortions are introduced by taxing agents in order to finance

[7] In a dynamic framework, when there is an externality, the time consistency problem appears even if there are no differences in preferences between private agents and the government. For an overview of this issue, see Cooper (1999). A problem of time consistency can emerge in a dynamic version of our model, so that the order of moves matters. Suppose that the government commits to subsidize technology adoption in order to achieve a Pareto efficient allocation, but moves after the private agents. Under the assumption that the investment implied in technology is irreversible, once the firm has chosen the frontier technology the government does no longer have an incentive to pay the subsidy. The firm would recognize this and the government would be powerless to affect technology adoption and, thus, to offset the production externality.

subsidies aimed at eliminating the distortions determined by production externalities. Tax rates become in fact endogenous variables and, in the presence of inefficiencies in the strategic interaction between the firm and the self-employed entrepreneurs, the government's taxation policies and their timing may alter agents' choices.

Moreover, as stressed in Chapter 2, there are several other ways in which government intervention can affect the firm's incentives to adopt a superior technology besides the tax system, that we do not consider. For example, regulations can be passed preventing former workers (managers) to start a new business, or accept offers from competitors, for a certain time period after leaving the firm, thus eliminating (or at least reducing the value of) the possible outside options. Furthermore — even though it is generally acknowledged that their efficacy is in many cases limited — patent protection schemes, by making it difficult (or costly) to copy a technology, reduce the value of the outside options insofar the production externality requires the use of some of the technology components to be effective (i.e. the possible spillovers are to some extent complementary to the specific technology components).

Finally, while throughout the dissertation the public sector does not play any role as a producer or consumer, in reality it is a heavy consumer (and, more generally, adopter) of technology. In this perspective, governments could substantially affect technology adoption directly, by means of their decisions. For instance, by adopting massively a frontier technology, a government might be able to increase the average skill level of the workers in the economy. This, in turn, would reduce the size of (technology-induced) externalities and, therefore, their impact on wages, thus stimulating the adoption of superior technologies by private firms.

7

Conclusions

In this dissertation we addressed the issue of technology adoption by emphasizing the effects of the interaction between technologies and wages on firms' technological choices. We have stressed the existence of a direct link between the choice of a technology and wage, caused by technology driven spillovers determining an upskilling of workers and entailing, in turn, an increase of their productivity and an improvement of their outside options. Insofar as the improvement in workers' occupational choices can transfer on wages, the adoption of superior technologies by firms determines an increase of the wages they must pay in order to retain workers. There is thus a double source of externalities generated by a firm's decision to adopt a superior technology — a positive externality benefiting workers, through the increase in their productivity, and a negative pecuniary externality imposed on the firm, via the increase in the level of wages it must correspond to workers — that can possibly discourage or dampen the adoption of the better technology.

We have shown in a simple general equilibrium efficiency wage framework that this can indeed be the case when a firm does take fully into account the impact of externalities in its decision problem. Due to the presence of production externalities (and of the associated negative pecuniary externalities), firms may never have an incentive to upgrade their techniques to the frontier and can remain stuck with old and inefficient technologies; a further variant of the lock-in problem.

The comparison of market allocations with the Pareto-efficient ones achieved by a social planner internalizing all sources of non-marketed relations has shown the possibility of technology misallocation, which introduces a clear scope for government intervention in order to overcome or mitigate market failure. We have shown that a policy maker is able to re-establish Pareto-efficiency by means of first-best (non linear) subsidization. Furthermore, when non-linear subsidies prove too cumbersome to be implemented, welfare improvements can always be achieved by means of second-best instruments as Pigouvian subsidies on technology adoption, while the effects of interventions on firms' labor demand are ambiguous in that either a (Pigouvian) tax or a subsidy can be welfare improving, depending on the relative impact of the subsidy on labor and technology.

The key ingredients behind the dissertation results are not new to the technology adoption and diffusion literature. The role of labor endowments and the effects of wages on technology choices have been carefully investigated, and the same holds true for the impact of market power and of strategic interaction. Nonetheless, the way they are mixed here originates quite different results from those obtained in other contributions, as can be appreciated from the discussion in Chapters 2 and 3. One such difference that is particularly striking is with the literature on vintage human capital — often referred to as providing for a major engine of technology adoption — where workers' skills play the opposite role. In fact, in our framework it is the existence of transferrable human capital — responsible for the emergence of production externalities — to generate a delay in the adoption of the frontier technology via its impact on wages, while in the human capital model it is specific human capital responsible for firms' lock-in in inefficient technologies, whereas transferability of knowledge would favor the adoption of superior technologies. Our model may also account for the fact that, even though the more intense users of existing technologies (the richer countries) are those having more to loose from the adoption of a superior technology according to the human capital model, they are the ones that adopt faster, consistently with the observed trickle down mechanism. As far as skills are more uniform in advanced economies, the impact of a superior technology on workers' outside options and hence on wages should be lower, which encourages adoption. The opposite occurs in poorer countries, where a more unequal and scarce distribution of technical knowledge (skills) discourages the choice of superior technologies, in contrast with the predictions of the vintage human capital theory.

It is worth emphasizing that this dissertation approach is consistent with the idea of complementarity between technology and skills and that of the existence of a direct nexus between technology and wages, two facts largely confirmed and stressed by the empirical evidence on technical change, at least since the late forties of the past century.

Moreover, although our static framework does not allow for a complete analysis of the point, our theory seems to be at least qualitatively consistent with several characteristics of technical change patterns found in the literature. First the S-shaped diffusion process of technologies. One can conjecture that the adoption of a technology is slow at first because it gives rise to significant externalities of the sort discussed in the thesis, so that the marginal benefits of choosing the frontier technology are overcome by the marginal increase in wages it entails. However, as the skills required by the technology become more abundant, they will no longer generate better outside options, thus having a lower (or no) impact on wages, and firms will be more willing to adopt. Finally, as is standard in the literature, the market becomes eventually saturated and the adoption rate slows down.

Similarly, the increasing uniformity of adoption rates among richer countries and the trickle down hypothesis advanced in the growth literature to explain the divergence in cross-country rates of adoption between industrialized and less developed countries can be interpreted in the light of our framework. As already noticed, more advanced countries are characterized by relatively more homogeneous economic conditions (for example, in terms of their human capital) than poorer countries. This can imply, on the one hand, that the adoption of a superior technology is more likely to spill over richer economies because of the greater homogeneity of the ex-ante technical knowledge (that renders new knowledge more transferable) but, on the other hand, the induced externalities can be less of a problem exactly for the same reason (they have a lower impact on workers' outside options and hence on wages). As far as the second effect dominates the first, production externalities may contribute to explain why technologies are first adopted in leader countries (and the increasing uniformity of their technological choices) and trickle down to less developed countries only at a later stage.

A major drawback of our framework is that it is a static one, which impedes a careful investigation of the issues of timing and implementation of technologies, and hence of their diffusion processes. To model the strategic interactions between firms and employees, and the ensuing externalities in a dynamic environment, is a priority for future research. A further addition will be to introduce uncertainty about the size of technology-induced spillovers and, consequently, of production externalities, that can provide a further rationale to explain the observed delays in the adoption of superior technologies along the same lines suggested by the real options approach. As firms are uncertain about the value of workers' outside options induced by their choice of technology — a value that can change over time due, for example, to changes in education and schooling, or to advancements of the technology frontier over time — they will adopt only when the expected benefits from adoption are well above the expected costs (i.e. the increase in labor costs), that is when the option is well in the money.

Finally and at a greater level of generality, by working out dynamic formulations of our static models, it will eventually be possible to provide for a natural framework to investigate the role of technology in explaining growth and fluctuations, in a setting largely consistent with the stylized facts.

Appendix A

Cobb Douglas Economy: Comparative Statics

A.1 The impact of γ on the equilibrium level of employment

We first show that the sign of $\frac{\partial N^*}{\partial \gamma}$ is undecided. From Equation (4.33) it follows that

$$\frac{\partial N^*}{\partial \gamma} = \underbrace{\frac{1}{1-\beta}\left[\frac{A\alpha^{\frac{\alpha}{\gamma}}}{\gamma}\left(\frac{\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-1}\right]^{\frac{1}{1-\beta}-1}}_{>0}\cdot$$

$$\left\{\underbrace{\left(\frac{-A\alpha^{\frac{\alpha}{\gamma}}\left(\frac{\alpha}{\gamma}\log\alpha+1\right)}{\gamma^2}\right)}_{<0}\underbrace{\left(\frac{\frac{\overline{v}}{c}}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-1}}_{>0}+\right.$$

$$+\underbrace{\frac{A\alpha^{\frac{\alpha}{\gamma}}}{\gamma}}_{>0}\left[\underbrace{\frac{\alpha-\gamma}{\gamma}\left(\frac{\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-2}\left(-\frac{\beta\frac{e}{c}}{(\beta\gamma-\alpha)^2}\right)}_{>0}+\right.$$

$$\left.\left.\underbrace{-\frac{\alpha}{\gamma^2}}_{<0}\underbrace{\left(\frac{\frac{e}{c}}{\beta\gamma-\alpha}\right)^{\frac{\alpha}{\gamma}-1}}_{>0}\underbrace{\log\left(\frac{\frac{e}{c}}{\beta\gamma-\alpha}\right)}_{?}\right]\right\}\overset{?}{\gtrless}0. \tag{A.1}$$

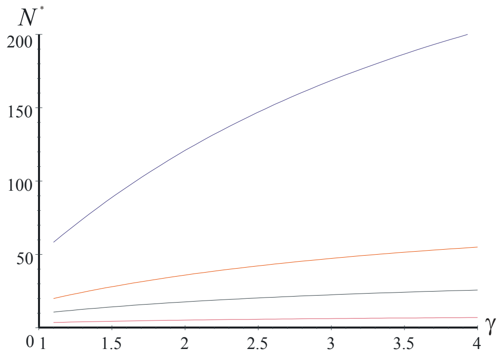

FIGURE A.1. The behavior of N^* for $\frac{e}{c} = 1.5$ (magenta line), $\frac{e}{c} = 0.75$ (black line), $\frac{e}{c} = 0.5$ (red line) and $\frac{e}{c} = 0.25$ (blue line)

It is immediate to observe that the sign of Derivative (A.1) is undecided, as it depends on the sign of $\log\left(\frac{\frac{e}{c}}{\beta\gamma-\alpha}\right)$, that in turns is affected by the values of the disutility of effort and monitoring technology $\left(\frac{e}{c}\right)$, and of the production function parameters α and β.[1] Moreover, there are no compact analytical conditions that characterize the sign of the derivative.

Focusing on the impact of changes of the disutility of effort and/or of the firm's monitoring, Figures A.1 and A.2 report experiments on the cross effects of γ and $\frac{e}{c}$ on N^* for the benchmark parameter set (4.31).

[1] In order to show that

$$\left(\frac{-A\alpha^{\frac{\alpha}{\gamma}}\left(\frac{\alpha}{\gamma}\log\alpha+1\right)}{\gamma^2}\right) < 0,$$

it is easy to prove that it can not be $\frac{\alpha}{\gamma}\log\alpha + 1 < 0$. Note that

$$\lim_{\alpha\to 0}\frac{\alpha}{\gamma}\log\alpha = 0 \text{ and } \lim_{\alpha\to 1}\frac{\alpha}{\gamma}\log\alpha = 0.$$

Moreover, it is $\frac{\alpha}{\gamma}\log\alpha < 0$ for all $0 < \alpha < 1$. From the first order condition of the minimization problem for such a function, we get its $\arg\min$

$$\frac{1}{\gamma}\log\alpha + \frac{\alpha}{\gamma}\cdot\frac{1}{\alpha} = 0 \iff \log\alpha = -1, \text{ i.e. } \alpha = \frac{1}{e}.$$

By evaluating $\frac{\alpha}{\gamma}\log\alpha + 1$ at $\alpha = \frac{1}{e}$, we obtain

$$\frac{1}{\gamma e}(-1) + 1 > 0,$$

which proves the claim.

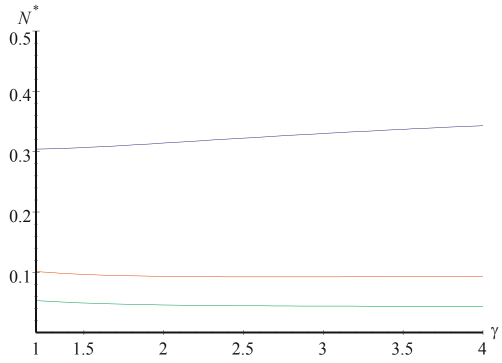

FIGURE A.2. The shape of N^* for $\frac{e}{c} = 7.5$ (blue line), $\frac{e}{c} = 15$ (red line), and $\frac{e}{c} = 22.5$ (green line)

As it is to be expected from standard economic theory, the employment locus shifts upwards the lower the disutility of effort, or the higher the probability to catch a shirker (i.e. the better the firm's monitoring technology). Furthermore, numerical experiments (see again Figures A.1 and A.2 for a qualitative illustration) suggest that there exists a threshold for $\frac{e}{c}$ (depending on the specific parameters configurations chosen: $\frac{e}{c} = 7.5$ in the case of the parameters set used here) such that below it a switch in the sign of the derivative is no longer observed and the derivative remains positive. Additional numerical experiments show that there exists a $\gamma -$ threshold as well, such that above it the equilibrium level of employment is increasing in γ, whatever the value of $\frac{e}{c}$.

The cross effects of γ and $\frac{e}{c}$ on the equilibrium employment and technology levels can be further appreciated in terms of the loci $n^*(T)$ and $t^*(N)$. Figure A.3 — drawing them in the $N-T$ plane for our standard parameter set (4.31) — shows the *positive* impact of γ (for low values of γ) on the optimal levels of employment and technology when $\frac{e}{c} = 0.75$. The loci represented with black lines correspond to the case in which $\gamma = 2$, while the red lines represents the same loci for $\gamma = 3$. It is immediate to observe that both the equilibrium level of employment and of

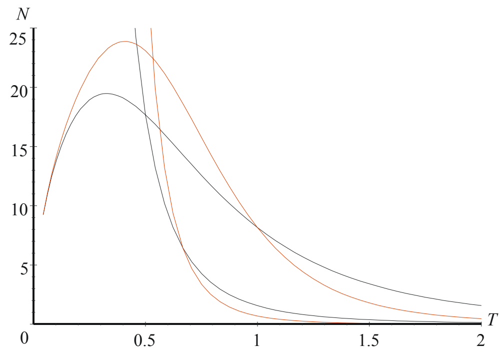

FIGURE A.3. The positive impact of γ on N^* and T^* when $\frac{e}{c} = 0.75$

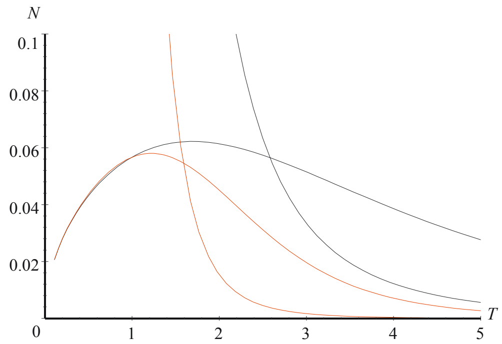

FIGURE A.4. The negative impact of γ on N^* and T^* when $\frac{e}{c} = 20$

the technology grade increase (from 17.68 to 22.5 and from 0.5 to 0.53, respectively) when γ increases (from 2 to 3).

Figure A.4 shows the same loci drawn for the same benchmark parameter set, but for $\frac{e}{c} = 20$. As it can be seen from the figure, in this case, an increase of γ (the black lines correspond to $\gamma = 2$ and the red lines to $\gamma = 3$) has a *negative* impact on the equilibrium levels of employment and technology.

A.2 The impact of α and β on the equilibrium level of employment

Inequalities (4.53) and (4.55) provide sufficient conditions to characterize the sign of $\frac{\partial N^*}{\partial \alpha}$ and $\frac{\partial N^*}{\partial \beta}$ respectively. More generally, however, the shape

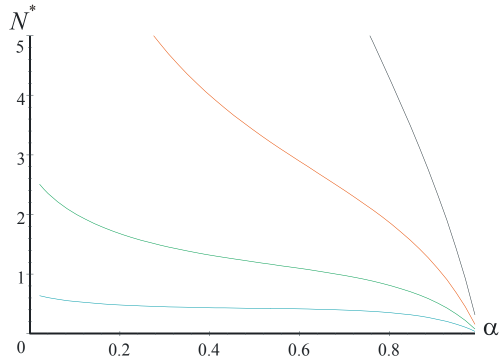

FIGURE A.5. $N^*(\alpha)$ for $\frac{e}{c} = 0.75, 1.5, 3, 6$

of $N^*(\alpha)$ and $N^*(\beta)$ is affected in a non-monotonic way both by the wage determination process (through the impact of γ and $\frac{e}{c}$) and by technological factors (through the quota spent by the firm in the labor input, β, and the one spent in the technology input, α, respectively), which renders impossible to fully characterize the behavior of labor demand, and to immediately assess the direction of the cross-effects at play. In order to illustrate this point, we do not attempt to provide an analytical characterization, limiting instead ourselves to investigate the joint effects of parameters γ and $\frac{e}{c}$ on $N^*(\beta)$ (and $N^*(\alpha)$) by means of numerical experiments.

Figure A.5, drawn for the benchmark parameter set (4.31), documents the behavior of $N^*(\alpha)$ following changes in the disutility of effort (and/or in the monitoring technology) affecting the ratio $\frac{e}{c}$. As it is to be expected, the locus $N^*(\alpha)$ shifts downward as the disutility of effort increases (or the firm's monitoring decreases), the black line in the figure corresponding to $\frac{e}{c} = 0.75$ and the cyan line to $\frac{e}{c} = 6$. The same holds true for the effect of $\frac{e}{c}$ on $N^*(\beta)$ as shown in Figure A.6, where we distinguish between different values of A to highlight the fact that they affect the shape of $N^*(\beta)$.[2]

[2]In the study of $N^*(\alpha)$, there is no need to distinguish between different values of A, since it does not affect the shape of the locus (see Equation 4.51).

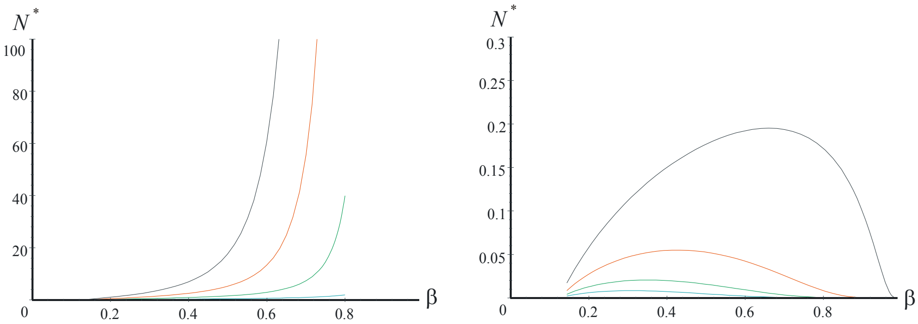

FIGURE A.6. $N^*(\beta)$ for $\frac{e}{c} = 0.75$, 1.5, 3, 6 and $A = 10$ (left chart), $A = 1$ (right chart)

As for the impact of γ on $N^*(\alpha)$, Figure A.7 illustrates the effects of changes in γ on the shape of the locus and on the equilibrium level of employment for different values of the disutility of effort.

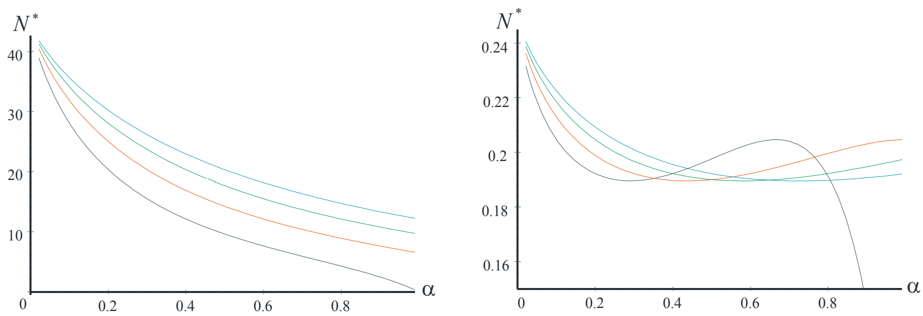

FIGURE A.7. $N^*(\alpha)$ for $\gamma = 2, 3, 4, 5$ and $\frac{e}{c} = 0.75$ (left graph), $\frac{e}{c} = 10$ (right graph)

Notice that when the disutility of effort is low (for example, at the level set in our standard parameter set, $\frac{e}{c} = 0.75$, used in the left graph), increases in γ — $\gamma = 2, 3, 4, 5$, with the black line corresponding to $\gamma = 2$ and the cyan line to $\gamma = 5$ — have a positive impact on employment for any α in the definition range; while, when the disutility of effort is high ($\frac{e}{c} = 10$ in the right graph), $N^*(\alpha)$ is no longer monotonic and increases in γ imply an increase in the values of α at which the (first) switch in the sign of $\frac{\partial N^*(\alpha)}{\partial \alpha}$ occurs. Note also that, for values of γ high enough, the sign of the derivative remains negative for all admissible values of α.

Figure A.8, whose upper charts are drawn for the base parameter set with $A = 10$, shows how γ affects $N^*(\beta)$ for different values of $\frac{e}{c}$ ($\frac{e}{c} = 0.75$ in the left graphs, and $\frac{e}{c} = 10$ in the right graphs). Notice that $N^*(\beta)$ is increasing in γ — from $\gamma = 2$ (black line) to $\gamma = 5$ (cyan line) — for all β when the disutility of effort is low ($\frac{e}{c} = 0.75$), while — coherently with the sign of $\partial N^*/\partial\gamma$ being undecided — the impact of γ becomes non-monotonic when $\frac{e}{c}$ increases (to $\frac{e}{c} = 10$ in the figure), although our numerical experiment suggests that the locus $N^*(\beta)$ shifts upward when γ increases. This tendency is confirmed by the two lower charts, repeating the same exercise for $A = 1$.

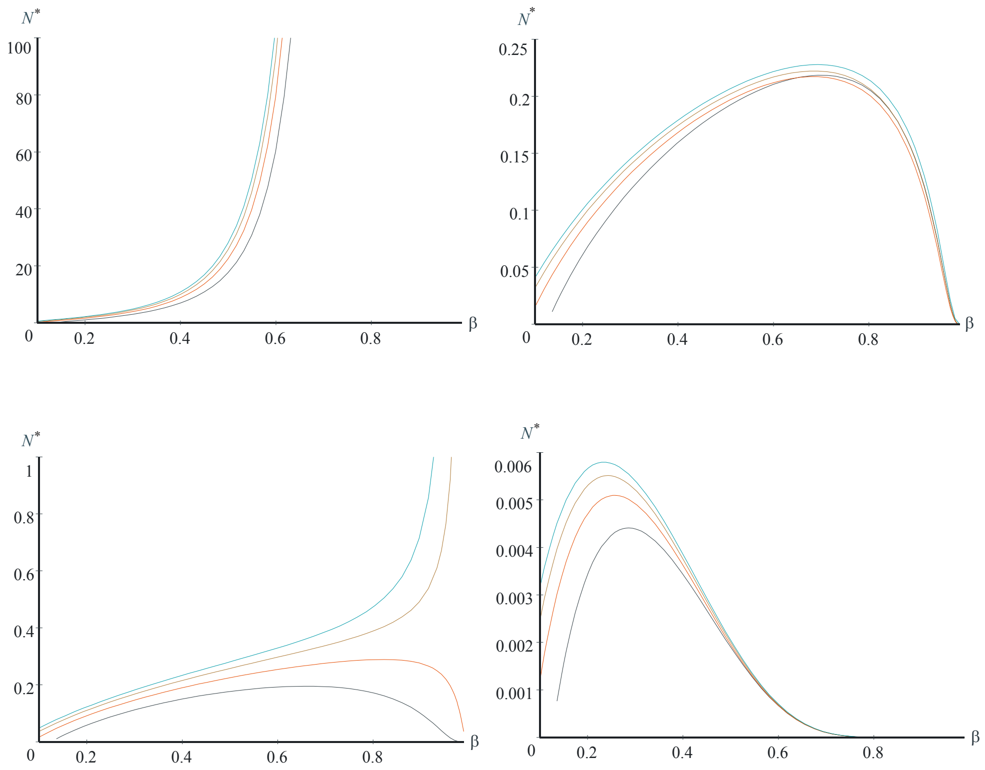

FIGURE A.8. Joint effects of γ and $\frac{e}{c}$ on $N^*(\beta)$

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