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MODELING SPECIALIZATION AND DIVISION OF LABOR IN CULTURAL EVOLUTION

Micael Ehn

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School of Education, Culture and Communication

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MÄLARDALEN UNIVERSITY
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Akademin för utbildning, kultur och kommunikation

Abstract

Division of labor and division of knowledge are so important and common in society today that it is difficult to imagine a functional society where everyone knows the same things and performs the same tasks. In such a society everyone grows, or gathers, and prepares their own food, makes their own tools, builds their own house, and so on.

Cultural evolution is the field of research that studies the creation and diffusion of ideas and societies. It is very uncommon for these studies to take into account the effects of specialization. This thesis will show that specialization is of great importance to cultural evolution.

The thesis is divided into two parts: The first is an introduction to studies of specialization and division of labor. The thesis begins with an interdisciplinary survey of the research on division of labor and specialization, including both theoretic and empirical studies. Next is an introduction to modeling specialization and division of labor. This includes a general framework and a number of basic models of different aspects of specialization and division of labor.

Part two consists of four papers. The first paper studies the interaction between specialization and cultural cumulation. The second and third papers examine cultural cumulation, specifically the circumstances under which cultural knowledge increases and how cultural knowledge is distributed in the population. The last paper is a mathematical model of how specialization of knowledge (i.e. higher education) leads to social stratification.

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Sammanfattning

Fördelning av arbetsuppgifter och kunskap är något så viktigt i dagens samhälle att det nästan är omöjligt att föreställa sig hur samhället skulle kunna se ut utan dem. Man kan också genom enkla observationer se att arbetsdelningen verkar fortsätta öka inom många områden. Ett exempel är matindustrin där halvfabrikat blir mer och mer vanligt och både färdigskivad ost och färdigskivat bröd har dykt upp i matbutikerna de senaste åren. Antalet personer som är inblandade i att se till att det finns bröd att köpa i butiken är enormt. Man måste odla säd, tillverka jäst, utvinna salt och sedan ska det fraktas, bakas och fraktas igen. Vart och ett av dessa moment är uppdelat i flera delmoment, som i sin tur utförs av olika personer. I tillverkningen och transporten används också ett stort antal maskiner, vilket i förlängningen innebär att ännu fler personer blir inblandade i att tillverka och underhålla dessa maskiner.

Att arbetsdelning är väldigt viktigt för ekonomin har man vetat om länge: arbetsdelning tog upp en stor del av Adam Smiths klassiska verk *The Wealth of Nations*, som kom ut 1776. Ekonomer har sedan dess studerat relationen mellan marknaden, transaktionskostnader och arbetsdelning samt hur arbetsdelning ökar produktionseffektiviteten. Ett aktuellt exempel på hur transaktionskostnaderna påverkar arbetsdelningen i Sverige är skattereduktionen för hushållsnära tjänster. Den gör att transaktionskostnaden för dessa tjänster minskar och därmed ökar arbetsdelningen, det vill säga färre personer städar själva.

Kulturell evolution är ett forskningsområde som studerar hur samhällen och idéer föds, sprids och dör, ofta genom att använda sig av matematiska modeller. Man tar dock ytterst sällan tar hänsyn till hur denna utveckling påverkas av arbetsdelning och fördelning av kunskap. Jag vill med denna avhandling visa att dessa faktorer är av stor vikt för kulturell evolution samt studera interaktionen mellan dessa processer.

Avhandlingen består av två delar. Den första delen fungerar som en introduktion till både empiriska och teori för specialisering och arbetsdelning. Den börjar med en kort introduktion till avhandlingen och de frågor som

den behandlar. Kapitel två består av en omfattande litteraturöversikt av den forskning som har gjorts om arbetsdelning i ekonomi, historia, sociologi och många andra ämnen. Denna översikt fokuserar på att ta ut de delar av denna forskning som är mest intressanta för dem som studerar kulturell evolution, men täcker även många andra aspekter av arbetsdelning. Översikten fungerar som en grund för de antaganden som används senare i avhandlingen.

Kapitel tre är en introduktion till matematisk modellering av specialisering och arbetsdelning. Det här kapitlet presenterar ett ramverk för formella studier av specialisering och arbetsdelning och fortsätter sedan med att gå igenom ett antal enkla modeller av olika aspekter av specialisering. Kapitel tre binder samman de olika studierna i avhandlingen i en större bild. Kapitlet visar också på ett antal framtida frågor om specialisering och arbetsdelning.

Del två består av fyra artiklar som studerar specifika frågor. Artikel ett studerar interaktionen mellan kunskap och specialisering. Artikel två och tre studerar olika aspekter av hur kunskap ackumuleras, vilket påverkar hur mycket specialisering som finns i samhället. Artikel fyra undersöker hur specialisering i form av utbildning resulterar i löneskillnader i samhället.

Acknowledgments

I am very grateful to have had the opportunity to work at the Centre for the Study of Cultural Evolution at Stockholm University. The diverse background of the people working there means that there is always someone to ask when you need help. This has contributed greatly to my education and I owe all of you my thanks.

A few people deserve special mention. First of all my supervisors: *Kimmo Eriksson*, *Magnus Enquist* and *Pontus Strimling*. Kimmo always provides insightful advice and has been extremely helpful in solving every problem I have encountered during the course of my research. Magnus is full of ideas and is a great source of inspiration. He has also taught me a lot about the philosophy of science during our weekly lunch meetings. Pontus has answered so many of my questions and has likely taught me more about cultural evolution than anyone else. During the last few years, I have shared my office with *Johan Lind*, and besides being a great roommate, he has helped me focus on what is most important in my research projects. I have worked extensively with *Anna-Carin Stymne*, who has been a great help with finding interesting empirical studies. Without her, the review in chapter 2 would not have been possible. Finally, *Sarah Wise* and *Fredrik Jansson* have been a great help in proofreading everything from abstracts for conferences to parts of this thesis.

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Part I

Studying Specialization, Division of Labor and Culture

Chapter 1

Introduction

Human specialization, unlike that in most animal species, is culturally rather than genetically determined. Instead of genetic differences, we specialize by distributing knowledge between individuals. This allows us to specialize to an extent unmatched by any other species and to adapt to new circumstances much faster than genetic evolution would permit.

Together with division of labor, specialization often greatly increases productivity making it possible for individuals to do things other than collecting food. This has a major impact on the development of technology and accumulation of knowledge, the cultural evolution in human populations. Adapting to local conditions, i.e. specializing, helped us inhabit just about every habitat on earth. Clearly, understanding specialization is necessary for understanding the evolution of both human culture and human civilizations.

1.1 Specialization and Cultural Evolution

This thesis studies specialization and division of labor in general; it focuses on the interaction with cultural evolution and accumulation of cultural knowledge in particular. The field of cultural evolution studies how cultural traits, i.e. knowledge, ideas or practices appear, spread and disappear. Cultural traits are often defined as information that is acquired by learning from others (e.g. Boyd and Richerson, 1985; Cavalli-Sforza and Feldman, 1981). Since this thesis considers the interaction between specialization, division of labor and culture, I am mainly concerned with cultural traits that are influencing, or influenced by specialization or division of labor. In this thesis, I will therefore restrict the term cultural trait to mean cultural knowledge that increases productivity when performing some task.

Carneiro (1967) shows that the order in which many organizational traits appear in societies as their populations grow is very consistent. Several of these organizational traits are specializations, such as merchants or full time craftsmen. Others are typical cultural traits, such as the calendar or code of laws. Carneiro concludes that these organizational traits are required for the population to grow past certain levels and that certain traits are required for other traits to emerge, indicating that specialization is very important for cultural evolution.

Traditionally, studies of cultural evolution have focused on the interaction between culture and genes, gene-culture co-evolution (Cavalli-Sforza and Feldman, 1981; Boyd and Richerson, 1985). One of the most common examples is lactose tolerance. The capacity for digesting lactose would not have spread in human populations unless the cultural trait of producing and consuming lactose products had not spread first (e.g. Itan et al., 2009).

Recently, research in cultural evolution has often studied cultural evolution as a process separate from genetic evolution (e.g. Strimling et al., 2009b,a). The argument for this approach is often that cultural evolution is much faster than genetic evolution or that certain cultural traits, such as one's opinion on fashion, do not affect gene frequencies. As we will see, the level of specialization and division of labor is very low in hunter gatherer societies. Extensive specialization and division of labor is therefore a relatively new concept in human history and have likely had little impact on human genetics. This thesis will therefore take the latter approach, studying cultural evolution separately from genetic evolution.

1.2 Origin of Specialization

In most theoretic work, division of labor and specialization are assumed to have appeared because of increased productivity, often due to comparative advantages (e.g. Smith, 1776; Yang and Ng, 1998). Often the process is described generally as follows: If one person is better at making arrowheads than hunting and another person is better at hunting, they can specialize, so that they both make the best use of their skills. Specialization makes sure we can utilize individual differences, both genetic and learned skills. Someone who makes arrows to trade for food does not have to learn advanced hunting skills; he can spend more time learning how to perfect his arrowheads instead. When he spends a lot of time making arrows he will become even more proficient and maybe even invent new tools or techniques to produce them faster (e.g. Yang and Borland, 1991). A market with several specialists of the same kind opens up for competition: the best arrowmaker will likely be able to charge more for his services. There is now an even bigger incentive to make better arrows. The larger market also makes it possible to have a wider range of goods: when the demand is high enough, merchants will be able to travel farther to acquire products not available locally.

While this seems like a plausible explanation, it is not consistent with the empirical studies. Trading of arrows for meat, or trade of any resource between individuals who could both produce the resource is not mentioned at all in empirical studies of hunter gatherers. The best hunter may give some of his prey away to the less fortunate, but not in a direct exchange for some other goods. Instead, exchange in hunter gatherers is often limited to trade for items that can not be produced locally. Specialization within the local group is limited to religious tasks and possibly leadership (Coon, 1948; Sahlins, 1978; Johnson and Earle, 2000; Spielmann, 2002; Seabright, 2004).

Seabright (2004) mentions that division of labor requires relying on someone else and that this is always a risk. I think this, together with the low cost (and therefore limited advantage) of learning how to perform all of the basic tasks in a small society, explains why specialization is so uncommon in hunter gatherers. While everyone would be better off because of the increased production in this example, there is also an inherent risk with specializing and especially with dividing knowledge between individuals. The arrowmaker does not know how to hunt, at least not very efficiently. If the hunter were to die unexpectedly, not only would his knowledge be lost, the arrowmaker would not be able to trade his arrows for food, so he is dependent on another individual for his survival. This is, however, just speculation. I have not found any empirical study that either validates or contradicts this hypothesis.

The increased risk can be avoided by increasing the size of the market, having several hunters and arrowmakers or perhaps even by trading with other groups. Relying on strangers will of course increase the risk, unless the group is self sufficient when it comes to basic needs. Under certain conditions, trading with others can actually decrease certain risks. A local drought will not be quite as severe when some food can be obtained by trading with other groups which have either not been affected or have other ways of gathering food. This requires a larger population, and hunter gatherer societies often consists of relatively small groups.

Once the efficiency in food gathering and other absolute necessities is high enough, there is more time for other pursuits, such as technological development and educating the population. Teachers help preserve and distribute knowledge efficiently in the society. As technology advances, even more occupations are introduced, since the number of tasks that requires extensive training increases and it is no longer necessary for everyone to have all knowledge available in the society.

1.3 Integrating Data and Theory

The description of the evolution of specialization in the previous section is based entirely on theory and speculation. Only by basing the assumptions of theoretic studies on empirical results and by testing the predictions of theory against actual data can we verify that the theory is correct. This is unfortunately not that common. In the study of specialization, much theory is put forward by economists and sociologists, while empirical studies are primarily performed by anthropologists, historians and archaeologists. This results in a dichotomy between theory and data.

The research in this thesis consists almost entirely of theory. However, in an effort to bridge the gap between theory and data I have worked with Anna-Carin Stymne to present an extensive interdisciplinary survey of both theoretic and empirical work on division of labor and specialization. The review is chapter 2 of this thesis and will provide both an introduction to the previous research in specialization and division of labor, as well as background information for the rest of the chapters in this thesis.

1.4 Mathematical Analysis

Mathematical models have been used in the natural sciences for a long time and made a huge contribution to our understanding of the world we live in. Mathematics is increasingly commonly used in the in social sciences as well. Mathematics provides a formal method of reasoning that can show exactly what result a specific set of assumptions imply, and at the same time requires that all assumptions be made explicit. This allows testing of hypotheses and is a great help when studying complicated systems. Mathematics also lets us focus on one or a few aspects of a complicated system and can tell us which set of assumptions that are necessary or enough to explain a certain phenomena.

Mathematical analysis has been the norm in the field of cultural evolution since it was founded (Cavalli-Sforza and Feldman, 1981; Boyd and Richerson, 1985). Even though, as we will see, the study of division of labor and specialization lends itself to at least some mathematical analysis, most of the theory for division of labor and specialization consists of verbal reasoning only. Since specialization and division of labor are of great importance for markets, they are of interest to economists, the field within social science with the longest tradition of using mathematics. Studies using formal models are therefore largely restricted to the interaction between specialization, division of labor and the market (Yang and Ng, 1998).

Specialization and division of labor interacts with a large number of other processes in a complex system. This makes using formal methods for analyzing the system necessary, but at the same time makes modeling the system more complicated. It is not immediately obvious how to create appropriate models which will increase our understanding of specialization and division of labor. Chapter 3 of this thesis investigates how we can model specialization by providing a general framework as well as a number of simple models of different interactions. The chapter is intended both as an introduction to creating models for specialization as well as inspiration and a basis for the papers in the rest of this thesis.

1.5 Papers in this Thesis

This thesis contains four papers, which are briefly described here. Paper 1 investigates the central question of this thesis. How do cultural evolution interact with specialization and how can we model this interaction? The paper concludes that specialization and cultural evolution interact through several feedback loops, such that cultural evolution is both a cause and an outcome of specialization. One of the findings in Paper 1 is that a larger amount of cultural knowledge leads to more specialization. *Social learning*, i.e. copying information from others rather than individually studying the environment in order to find information about it, is a central process in cultural evolution. Paper 2 establishes the conditions under which social learning can lead to increased cultural knowledge in a population. It is found that cultural knowledge increases with more social learning only when social learning is significantly more efficient than individual learning.

More complex solutions to problems are both more costly and take longer to learn, which increases the advantage of specialization. Paper 3 studies how different combinations of social and individual learning affect how complex solutions can be maintained in the population. Of the strategies considered in this paper, a strategy known as *critical social learning* is the most efficient at maintaining highly complex solutions under the widest range of parameters. The critical social learner uses social learning to acquire a solution and then, if the solution is not efficient enough, refines it using individual learning.

In Paper 4, I study the decision of whether to invest in learning more advanced skills, i.e. to become more specialized. When individuals value future payoffs, such as those that come from investing in increased specialization, lower than immediate, specialization in knowledge will lead to social stratification. The model presented in Paper 4 is a good predictor of social stratification depending on levels of education and is validated using public statistics from seven different countries.

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Chapter 2

Theoretic and Empirical studies of Division of Labor and Specialization— An interdisciplinary survey

With Anna-Carin Stymne

Many authors (e.g. Smith, 1776; Young, 1928; Yang, 1994) argue that understanding division of labor and specialization is very important for understanding increasing returns and even basic economy. This however is still a very narrow view of the influence of division of labor. The increased efficiency that can be had by dividing a task into smaller tasks performed by different individuals is one of the main reasons that cooperation is beneficial. Understanding how cooperation generates benefit might be one way to solve or avoid problems such as free riding (Calcott, 2008).

Some even go as far as to argue that modern humans' capability for division of labor is the cause that Neanderthals became extinct when modern humans spread across the world (Horan et al., 2005). They present a model which is based on the assumption that individuals can be either skilled or unskilled hunters. Skilled hunters obviously are more efficient. Since humans traded to a larger degree than Neanderthals, they could make greater use of their skilled hunters by allowing them to become specialized on hunting and therefore receive more food, which results in more offspring.

Even though there are a large amount of studies on division of labor, there are still many areas of this phenomenon that remain unstudied, or where results in different studies contradict each other. For example, what is the relation between specialization, population density and technological development? Adam Smith's *The Wealth of Nations* (1776) covered many aspects of division of labor, but since then, there has been a lack of interdisciplinary work on this subject. In this paper we will provide an interdisciplinary overview of some of the most interesting studies, both theoretical and empirical. We will try to answer questions such as: in what form did division of labor and specialization first establish among humans? How did it evolve, in what order did specialists appear? How did and do different human societies and cultural groups deal with division of labor and how does it vary across societies?

2.1 What is Specialization and Division of Labor

The terms *specialization* and *division of labor* are commonly used in the literature. Yet, the terms are not very well defined and are sometimes used as synonymous. Here we suggest and use the following definitions:

Specialization refers to an individual or another single entity such as a clan or a nation. Such an entity specializes if it focuses on one or a few tasks or options and neglect others. For example, a society or an individual can be specialized in fishing, which would mean that they do not hunt extensively. We can distinguish between:

- Temporary and consistent specialization
- Unskilled and skilled/trained specialization

Division of labor can only occur in a group of individuals or in a group of some other entities like a group of states. Division of labor occurs when separate entities perform different tasks with some coordinated aim. We can distinguish between:

- Temporary and consistent division of labor
- Whether the division of labor utilizes specialists or not

A separation of task specialization and individual specialization is suggested by Gorelick et al. (2004). Some tasks are done by a single or a few individuals (such as cave-painting, healing or horn-playing), but the individual performing the task is not an individual specialist because he also perform a lot of other tasks for subsistence such as hunting and gathering. In this case, the task is specialized for a specific individual, but the individual perform a lot of other tasks and is not individually specialized in one or a few tasks. It is also common to distinguish between *independent* and *attached* specialists. Independent specialists produce goods independently and often for a market, usually they also acquire the raw materials for themselves. Attached specialists on the other hand work for some patron or elite, usually for a wage. They are often provided with raw materials and a workshop by their employer.

2.1.1 Organization and Division of Labor

Division of labor can be organized in different ways. In the famous needle fabric example by Adam Smith, a work process is organized by dividing the labor of manufacturing needles into seven separate tasks, performed by seven individuals. When dividing the labor efficiently, the seven workers produce much more than if everyone would produce needles on their own.

All kinds of division of labor among humans requires some kind of agreement (a deal or commitment) and organization, even though no one is in charge of the whole process, especially not in modern complex societies (see Seabright, 2004). There are tasks that require cooperation and there are tasks that individuals can do alone. Some tasks are more difficult to divide than others, especially those that are dependent on season, such as many agricultural tasks. Division of labor within tasks that require cooperation, such as advanced hunting or boat- and house building likely appeared earlier than division of labor that require some kind of organized exchange systems such as a market. Organization within a firm, a community or even a family is of course important when studying division of labor. In all societies there are areas that would gain on division of labor but yet are not divided, or divided in an inefficient way, in the absence of leadership, proper organization or regulation.

2.1.2 Different Kinds of Division of Labor

Division of labor within family is an important, elemental economical unit of society (Becker, 1981; Johnson and Earle, 2000; Sahlins, 1978) and is a broad line of research with many studies. The division by sex is universal, but differ a lot from society to society (Murdock and Provost, 1973). In most human societies there are norms, taboos and rules for division of labor by sex. Many tasks are associated with a specific sex. These norms and rules are either explicitly formulated, sometimes in written laws, or implicitly learned and transmitted (Murdock and Provost, 1973; Hadfield, 1999).

Becker discuss sexual division of labor, assuming different comparative advantages for men and women. His theory is applied to families, regarding them as small firms that produce goods for self-consumption or the market (Becker, 1981). The theories, however, are applicable also in a wider sense as there is no reason that a small community or even an entire country cannot be regarded in the same way.

Another well studied subject is the social division of labor between agriculture and crafts. Marx and Engels stimulated research on the division of labor of those who organize labor (intellectual work) and those who perform it (manual work). Different authors often make their own categories. For example, Gershuny distinguishes between division of labor by different industries and trades, paid and unpaid activities and between different kinds of people Gershuny (1983).

2.2 Basic Observations

2.2.1 Productivity

Increased productivity is a well known effect of division of labor and is axiomatic in just about every theoretic paper on division of labor. Smith attributes this increase to three things. First, when someone is doing the same task all day, he will become better at it than if he had other tasks to perform as well. The second reason is that time is lost when moving between different tasks. Finally division of labor facilitates the use of machinery, which greatly improves productivity

2.2.2 Specialization and Population Density

There are some empirical surveys analyzing the relationship between population size, population density and the amount of occupations in society, all coming to the same conclusion, population density and the number of occupation in society have a high correlation (e.g. Carneiro, 1987, 1967; Naroll, 1956; Bonner, 1993, 2006; Denton, 1996)

According to Spencer, specialization increases when society becomes more voluminous and covers different climate and geographical conditions (from Durkheim, 1933, p. 206). One of the most quoted insights from Adam Smith's text is that the extent of the market depends on the division of labor. This insight was later added to by Young (1928), who argue that "the division of labour depends upon the extent of the market, but the extent of the market also depends upon the division of labour".

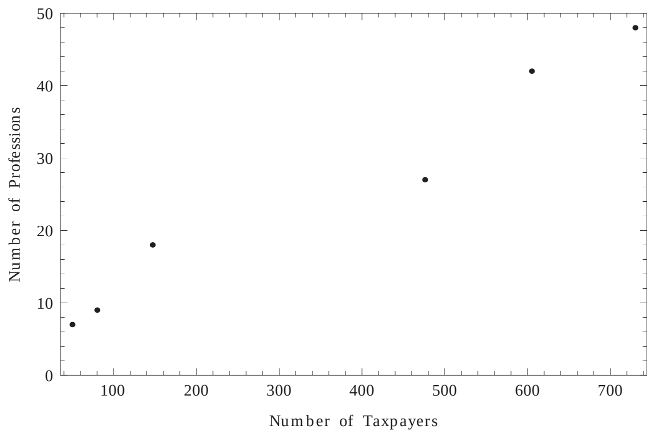

Figure 2.1: The correlation between the number of taxpayers (population size) and the number of occupations (indicated by occupational surnames) in medieval towns (Copenhagen, Malmö, Husum, Tönder, Sönderborg and Schwabstedt) in Denmark 1504-1577 (data from Hybel and Poulsen, 2007).

Emilé Durkheim concludes that the population volume causes division of labor and not vice versa. Just as the differentiation process into different species allowed more individuals to coexist, division of labor in human society makes higher population densities possible. When the population density becomes high enough, there is a requirement for specialization, to find new niches and be able to inhabit new areas (Durkheim, 1933).

Baumgardner (1988a) created a model that shows how demand, size of the local market and competition affects the degree of specialization in workers. In his model, workers can choose the amount of different goods to produce and it is assumed that a higher specialization (fewer types of goods) yields higher production. Workers want to produce as much as possible, and therefore would like to specialize, but there is also only a certain demand for every type of goods, which gives a limit for how specialized an individual can be. Thus, if there is only one worker in the market, his level of specialization will increase with the population while it will decrease if the worker has more time. Baumgardner shows that cooperation will result in a higher level of specialization than competition, which result in overlapping activities. However, competition might result in a higher consumer surplus. Specialization will increase with population, regardless of cooperative or non-cooperative behavior. If the population increases while the demand is held constant, specialization will still increase if the workers cooperate, but decrease if they compete.

Baumgardner also performed an empirical study to compare the results with his model. The study shows a significant relation between population and the number of physicians and their level of specialization, which was determined by counting the number of different conditions they treated. He also tried to determine which of the cooperative and the competitive setting matched reality best, but was unable to do so as some tests indicated cooperative and other indicated competitive behavior (Baumgardner, 1988a,b).

2.2.3 The Increasing Amount of Specialization

The increased differentiation of functions in society is often commented in the literature (e.g. Smith, 1776; Durkheim, 1933). The increasing number of specialists in society is so obvious that there has been few surveys actually measuring this universal fact. The studies that measure division of labor over time usually do so as a part of a larger study on economic development, social complexity or social mobility. However they are all coming to the same conclusions: increased occupational differentiation in society over time (e.g. Carlsson, 1966; Hybel and Poulsen, 2007; Lindberg, 1947; Denton, 1996).

Most of these studies count the number of occupations or surnames that indicate a specific occupation, which of course has some problems. The largest of those problems is that it is very hard to know what an occupational title really says about what tasks are performed by that particular individual. It is also common for workers to have several occupations, but just one of them might appear in the data, and this fluctuates over time, as shown by the history of farming and the history of firms (Britnell, 2001; Bengtsson and Kalling, 2007). The occupational surnames might also stay even if their bearers do not have that profession. The surnames show increasing differentiation, but this is not necessarily the same thing as increased specialization (Britnell, 2001).

Figure 2.2 shows the increasing division of labor over time. This graph illustrates the diffusion process for the craft professions by counting the proffessions as they become visible in the historical sources, starting with the smith (data from Hybel and Poulsen, 2007). The new occupations are added as the name shows up in different kind of historical sources. This is one way to show the direction of the differentiation, studying the differentiation over five hundred years, into more and more different specializations of the professions (unfortunately there is no reliable data available on the population size for the same period).

As can be seen here, there is no sign of a decrease in the number of occupations, even during the 14th century, when there was a big decline in

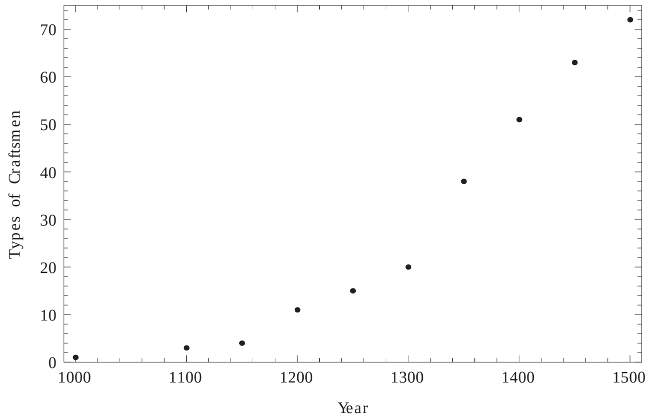

Figure 2.2: Differentiation process. Number of different occupations accumulating in Denmark, counted as they become visible in historical sources from 1000-1520. Plotted after Hybel and Poulsen 2007 (data from Hybel and Poulsen, 2007).

the European population. There is a lack of sources that show the number of occupations over time, especially from collapsing societies and periods when the population decrease. There are also few projects trying to combine empirical data from different surveys, especially across disciplines, to get a broader picture of long-term universal trends of specialization.

To our knowledge, there is no empirical evidence that the number of occupations drop significantly just due to population decrease, such as famine. Specialization seems to be linked to the internal organization of a society and if the organization and number of institutions of a society is intact, most occupations would be able to survive even if population density falls. If on the other hand there is a collapse of political order and institutions, such as when a society is divided into smaller parts, there will likely be loss of occupational specialization and technology (Tainter, 1988).

2.2.4 Limiting Factors

Transaction cost, or market efficiency, is determined by many factors, such as laws that aid or hinder trade, existence of money, supply and demand. One of the most important factors is distance, both in terms of transportation time and cost, which means that population density and technology will have a large part in determining how much specialization can be observed in a specific area. This was also noted by Adam Smith, who observes that areas with a higher population density, as well as coastal areas, will have more specialists (Smith, 1776).

Becker and Murphy argue that since it is very common to find several persons with identical specialization within the same city, division of labor cannot be limited mainly by the extent of the market. That would imply that these people with the same specialization should divide the tasks between them whenever possible. They take this as evidence that the main reason for the ever-increasing level of specialization is the increase in knowledge and that *coordination costs* is what limits it (Becker and Murphy, 1992).

2.3 Cooperation and Society

In his book *The Company of Strangers*, Seabright (2004) discusses how our economic system can work the way it does. Today a simple shirt is assembled by perhaps a hundred persons scattered throughout the world and each of them perform their small part of the work. This process, with an extreme division of labor and specialization, works without someone being in charge of the whole process. Seabright calls this "tunnel vision"; each person is paid for his small contribution and does not see, or care about, the whole process. Adam Smith (1776) also commented that a worker will have lesser insight in a common goal of society, and that division of labor and extreme specialization by routinizing work leads to alienation and uninformed workers.

2.3.1 Societal Development

Increasing division of labor and specialization tend to go hand in hand with societal development. As Adam Smith puts it: "what is the work of one man in a rude state of society being generally that of several in an improved one" (Smith, 1776). Carneiro suggests that several specialists, such as merchants, architects, craft specialists, as well as traits that help increase specialization, such as code of laws, roads connecting settlements and markets are required to maintain a certain population density. He also performs an empirical study which clearly show that these traits appear as society develops (Carneiro, 1967). This was also noted by Tainter, who lists decreased division of labor as one of the signs of a collapsing society (Tainter, 1988). Money is of course another consequence of division of labor, since there is no reason for it before trade. It is also something that makes trade much more efficient and results in more division of labor.

In many cases, specialization also lead to social stratification. The first signs of marked social stratification in archaeological studies are from the bronze age, when specialized leaders gain control over common resources (Gilman, 1981). See also paper II of this thesis for social stratification due to specialization in knowledge in modern societies.

It has also been suggested that division of labor is behind the decrease in average family size that we can observe in industrialized countries. Since families produce less resources for their own consumption and instead buy the necessities on a market, their benefit from economies of scale decreases and one of the reasons for having a large family disappears (Locay, 1990).

Several studies using mathematical models conclude that specialization increases average income (Zhou, 2004; Yang and Borland, 1991). This is of course because these models generally assume some advantage in total production when specializing.

2.3.2 Social Optimum

It is common for models of specialization to assume that individuals incur some personal cost for choosing to specialize. Davis suggests that there might be an external cost for specializing. In modern societies it is not uncommon for the government to pay for at least part of the education. When society provide for the education, there is a risk that individuals will tend to over specialize to earn higher wages, causing higher than optimal costs for society (Davis, 2006).

Kim (1989) published a model in which the level of specialization is lower than the social optimum. Workers in the model make two choices. The first is how much time to spend on education and the second is how many areas to study during this time. The amount of time spent on learning each activity determines the workers productivity within that activity and a higher number of activities increase the chance to find a suitable job. When firms hire employees with skills that don't match that firms profile, they incur a cost for reeducating the new employees, so they prefer to hire employees with a matching education.

The amount of available jobs, which is decided by market size and demand for labor, will have a big impact on the individual's choice of specialization in this model. With many available positions, individuals will focus on learning a few activities well since they likely will be able to find work anyway and a higher skill in a specific activity increase their wage. If there is a lack of available work, individuals will try to learn many activities instead, to maximize their chance of finding a job. Because much of the time spent on learning several activities is just to be able to get a job, it is wasteful from the society's perspective. It would be better if more time was spent on increasing individual skill instead (Kim, 1989). This is also indicates that coordination costs are what limits division of labor, if there was a better way to coordinate, the individuals could spend more time on specializing within one field instead.

The model might explain variations over time in the number of professions held by individuals as mentioned in studies of the history of farming and the history of firms (Britnell, 2001; Bengtsson and Kalling, 2007). In periods of recession, there is usually a lack of available work, so specialization should go down somewhat. In booming times there are plenty of work, so very specialized individuals will make a lot of money. On the other hand, it is common for universities to see a higher number of applicants during recession.

2.4 Cultural Evolution

2.4.1 Innovation

Increased innovation rate is also considered to be an effect of division of labor. This is because individuals are more likely to come up with ideas for machines or tools that simplify their work when they spend all day doing the same thing. Innovator as a profession is also discussed. It is believed to have come after industrialization, when producing machines became a separate industry and machines became too advanced, so that single individuals could not design them themselves (Smith, 1776). Of course, there is a codependency between technology and specialization. Many technological innovations created by specialists create new professions, which requires more specialists (computers for example).

There is also an intricate relation between population size and technological advances, that might be due to specialization. Specialization is required to keep a high level of technological advancement, since at a certain level it is impossible for every single individual to have all the knowledge available in the society. If the specialists were to disappear, the technology would likely be difficult to maintain. There are several examples of a decline in technological advancement correlated with a fall in population density, and likely also specialization, such as the Eastern Island and Tasmania (Diamond, 1999; Tainter, 1988; Kremer, 1993). One very extensive study tries to determine the rate of technological change, population size and density over a long time (one million years) and find a very clear correlation (Kremer, 1993).

Since it is not uncommon for innovations within one field to make use of technology developed for another purpose, if specialization increase the chance of making new innovations, the rate will be increased even further by new innovations that combine the different fields. Mokyr give some examples of such cross-fertilization: "Advances in metallurgy and boring technology made the high-pressure steam engine possible; radical changes in the design of clocks and ships suggested to others how to make better instruments and windmills; fuels and furnaces adapted to beer brewing and glassblowing turned out to be useful to the iron industry; technical ideas from organmaking were applied successfully to weaving" (Mokyr, 1990, p. 281).

2.4.2 Origin of Division of Labor

After Adam Smith, it is the effects of division of labor, positive, as economical growth and negative, as social stratification, that have been given most attention. Much fewer studies on the origin of division of labor are available.

Adam Smith believed that humans have a propensity to trade, which according to him is a necessary consequence of reason and speech. It is this propensity that gives rise to division of labor. When an individual makes some product, such as bows and arrows, better than others, people will offer to trade with him. He will then gradually spend more time at producing bows and arrows instead of hunting. After some time, he will realize that he will receive more meat from trading his products, than if he goes out to hunt himself.

Smith stresses that individual differences are not the cause of division of labor, but rather a result. In Smith's view there is some variation in human behavior or randomness that initiate the specialization process, then the variations reinforces into real differences in skill and knowledge. Some kind of predisposition or human drive for dividing labor and trading are also mentioned by several other authors (Ridley 1997, from Johnson and Earle 2000; Durkheim 1933).

Some argue that human reason and problem solving abilities give rise to the insight of the advantages of division of labor (e.g. Bonner, 2006). Most common of all is to assume that it is just a consequence of the fact that it is advantageous in many cases, making division of labor the natural consequence of technological development or economic progress (e.g. Becker, 1981; Yang and Ng, 1998). Becker was first to use mathematical models and formal reasoning to show how these advantages result in division of labor. He covered comparative advantages, economies of scale and learning costs (Becker, 1981).

Much of the recent work on the evolution of division of labor, expanding on Adam Smiths theories is from Yang and coworkers, (Yang and Ng, 1998; Cheng and Yang, 2004; Sun et al., 2004). Their work often contains models where individuals in a society both consume and produce goods, some of which they might buy or sell at a market. These models mostly depend on trade efficiency and some kind of economies of scale. Thus, production increase with division of labor, but it will be limited by transaction efficiency. With a very low efficiency, the society will be in autarky and with extremely high efficiency there will be a total division of labor. With the assumption that efficiency increase over time, e.g. due to increasing population density or technological development, these models will exhibit increasing division of labor over time, from autarky to a total division of labor.

There is one model that can explain the evolution from autarky to a society with highly specialized individuals, by means of learning by doing. The process begins with a society where everyone provides for themselves, since transaction costs are too high for specialization to be advantageous. Learning by doing results in a higher productivity, which will eventually make some specialization worthwhile. When the number of activities performed by each individual decrease, the accumulation of skill by learning by doing will accelerate, resulting in more and more specialization (Yang and Borland, 1991).

2.4.3 In What Order do Specialists Appear?

The Origin of Individual Specialists

Anthropological and archaeological research has been dealing with the transition from subsistence economy to production for a market. Empirical data indicate that this process often begin with a slow transition from attached or part-time specialists to independent, full time specialists. There are variations though, in Ancient Mesopotamia indications are strong for independent and attached specialists to have evolved simultaneously (Brumfiel and Earle, 1987). For the development in Denmark there are observations of a transition during the period 1000-1500 from attached craft specialists and female artisans working within a household (e. g. weavers), to independent male craftsmen (Hybel and Poulsen, 2007).

Specialization by Industry

A lot of research has been dealing with the appearance of specialized craftsmen. The appearance of full time artisans and the differentiations and development or adoption of different industries, such as agriculture, pottery and metallurgy often indicate economical growth and social development. Ethnographic data implicate that healers (shamans) are the only specialist in low-density family band societies. In societies with higher population density the second specialist to evolve is the leader (Coon, 1948; Seabright, 2004).

Gordon Childe argued that prehistoric bronze smiths were the first attested full time specialists (Chapman, 1996). The adoption of advanced metallurgy required specialists. The first metal items seem to be more symbols of wealth and prestige and as such defined as luxury goods rather than substantial (Anthony, 1996).

Do Specialists Evolve from Geographic Specialization?

One of Childe's interests was the rise of a more advanced division of labor and especially craft specialization. He studied the exchange between cultures, were the production often was dependent of geographical location, and the access of products such as salt, chert, gemstones and shells. According to Childe, this production did not resemble anything that could be called specialization. Most of the members in the societies were active in the production and the production was not substantial (Wailes, 1996). Trade with this kind of geographically determined products, in the literature often called "valuable goods", is universal (Coon, 1948). Areas often specialize in manufacturing and processing locally found valuables for trade, such as shell beads (e.g. California, Arnold, 1994).

2.5 Societal Development

To see how specialization is influenced by what kind of subsistence is used by a society, Lenski and Lenski (1978) used anthropological data to compile a table over the proportion of specialists in different fields grouped by subsistence type in the society.

Figure 2.4 clearly show that the amount of specialization increase when societies become more advanced. The data from Lenski and Lenski (1978) also includes metalworking which, when present, is always performed by a specialist. This supports the hypothesis that metal working is a field that requires specialists.

We will here present how division of labor appears in societies in different evolutionary stages. The categorization by Johnson and Earle in their book *The Evolution of Human Societies* will be used, but our survey will only cover the first two, which are of the most interest for studying the origin of specialization. The different stages are defined by socio-political organization and correlate well with population size, they are: The family level group, local group and region polity (Johnson and Earle, 2000).

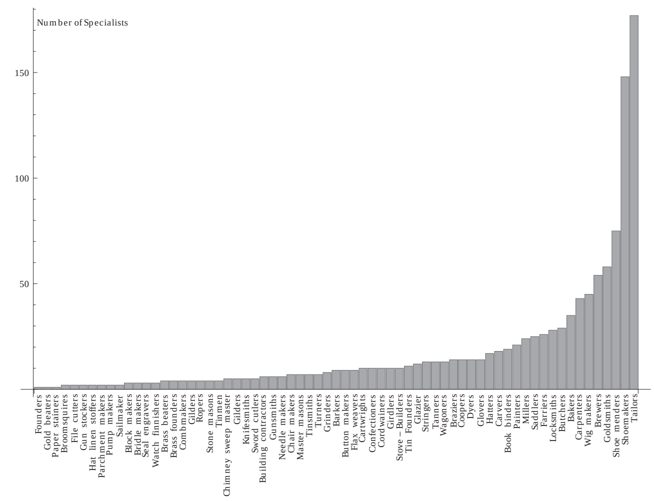

Figure 2.3: One interesting measurement is the frequency of each occupation. Of course, some occupations are more common than others. Large cities have a greater number of uncommon occupations. In Stockholm 1740 − 1741 there were 177 tailors, but only 2 sailmakers. (data from Söderlund, 1943).

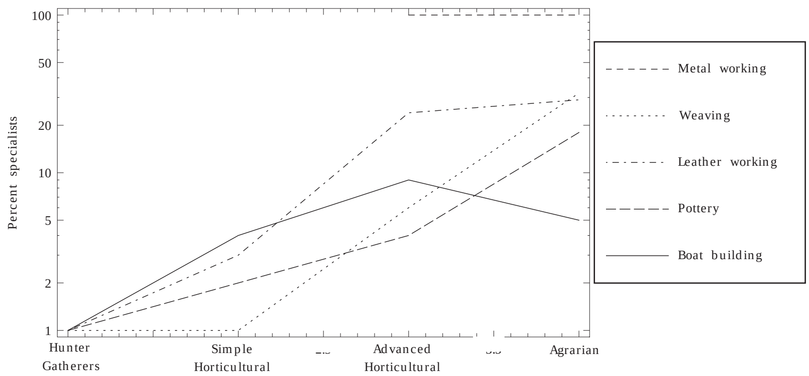

Figure 2.4: Amount of specialization in different societies, grouped by type of sustinence (data from Lenski and Lenski, 1978, p. 99).

2.5.1 Family Level Group

The social organization on the simplest institutional level is the family level group, or what Service calls "simple family bands". These societies are characterized by division of labor based almost exclusively on age and sex. Modern societies of this type are living in areas with low population density and are mostly hunter and gatherers, but some are farmers, as the Machiguenga (horticulturists, living in the rain forest of the Amazon in Peru) and the Nganasan (living in Siberia, with domesticated animals) (Johnson and Earle, 2000, p. 90).

Division of labor, other than according to sex and age, seems to occur only when absolutely necessary or when the advantages are great and the distribution of surplus is regulated and supervised. In other situations, it seems as if the losses from fighting over surplus will be greater than the gain in production and efficiency that would have been the outcome. In general, mostly families provide for themselves, both food and tools. The only exception seem to be healing.

Division of Labor by Sex and Age

What distinguishes division of labor by sex in mobile, family-level foraging societies is that there is usually a strict separation of tasks into a female sphere and a male sphere. Exactly what tasks are performed by men and which are performed by women vary from society to society, but there are a few trends. For example hunting large game is almost exclusively done by men in foraging societies and most gathering and childcare is done by women (Murdock and Provost, 1973; Johnson and Earle, 2000, p. 76).

Individual Specialists

Carleton Coon suggests that a healer is a part-time specialist in family band societies. The healer in these societies takes care of a combination of religious, social and medical functions. The way shamans and healers in family group societies are described in ethnographic sources (Coon, 1948), they are certainly task specialists, as the tasks they perform is only done by a few individuals. They are not full time specialists however, they also have to perform other tasks for self subsistence, even though they often receive gifts and privileges in exchange for their services.

Exchange

The !Kung share meat in the camp, which consist of several families living together. Hunting parties consist of 1-4 men. Sharing is important and prestigious among !Kung. Arrows are exchanged among hunters, so that a hunter can let another hunter make an arrow for him, but there are no specialized arrow makers. If a hunter is successful he is supposed to share meat with others. Highly skilled hunters that over a longer period share more meat than others will have greater respect and enjoy certain privileges, such as being allowed to have more than one wife (Johnson and Earle, 2000).

The sharing in small-scale societies is usually not associated with any requirement for reciprocity. This can however still be regarded as some kind of trade, as each individual is expected to contribute after ability (Sahlins, 1978, p. 194-200).

The most commonly traded goods in these societies are body-paint materials and other valuables for rituals, feasts or aesthetic objects. Trade can be long-distance, especially for societies living in harsh climate such as Inuit's that trade soapstone for lamps from great distance (Coon, 1948).

Complex Division of Labor

The Machigunega fish-poisoning involves between two and ten households, a leader controls the activities, men build dams, women construct weirs all with a complex division of labor (Johnson and Earle, 2000, p. 108-109). Cooperation on tasks both between and among families seems to occur only if absolutely needed or when bonds are very close. Families among the Machiguenga have their own gardens, prepare their own food etc. (Johnson and Earle, 2000, p. 107).

2.5.2 Local Groups

Local groups are societies organized in larger groups that extend simple family bands. Population size and density are higher than in family level groups, the groups are divided into subgroups, differing in number from two to twenty (Johnson and Earle, 2000, p. 123). The society becomes more sedentary; villages or hamlets are established, were the inhabitants, in most cases, live the entire year. Division of labor becomes common in large-scale projects, warfare and ceremonies (Johnson and Earle, 2000, p. 123-124).

Division of Labor by Sex and Age

Division of labor by sex increases in the sense that the society gets more divided in male and female spheres and masculinity and power is glorified. The division is not quite as strict however, it is more a matter of who is in charge of different tasks. Ceremonies of different kinds are important and men and women have different roles and contribute in different ways. Warfare and weapons manufacturing are exclusively male areas. Women make a greater contribution to food production and manage the household economy (Johnson and Earle, 2000, p. 129-131).

Individual Specialists

Leadership is getting more formalized in settlements with higher population densities and larger groups living together than in family group level societies. Task specialization, especially ceremonial activities, is linked to specific individuals and formalized.

The leaders in local group societies are still dependent on charisma and are somehow chosen by the group. The leader have a function as a coordinator in ceremonies, which become more important. The ceremonies also require more and new kinds of goods, such as shells, feathers and food. New services, such as tattooing, are also required. The ceremonies are financed through an intensified production and division of labor. Several other tasks associated with the ceremonies, such as tattooing, music and decoration are also formalized and assigned to specific individuals (Johnson and Earle, 2000; Spielmann, 2002).

Exchange

Internal exchange of goods is rare, but larger ceremonial meetings that also involve other groups occur more often and at these meetings there are some exchange of goods (Johnson and Earle, 2000). In some cases there is geographical specialization due to availability of resources, or just by choice. There are no specialized merchants, though the leader of a group often has an important role in trade and in distribution of food and valuables.

2.5.3 Chiefdoms

Division of labor in larger and more complex chiefdoms is characterized by a big increase in the amount of administrative positions. Administrative and craft specialists emerge at an increasing rate when the society gradually becomes more complex and population density increases. To be able to maintain this in the more complex chiefdoms, the subsistence is usually provided by intensive agriculture.

The division of labor by sex continues to be important among peasants, as the base of the subsistence economy continues to be the family (Johnson and Earle, 2000).

2.6 Discussion

There is research on division of labor and specialization in a wide array of fields, unfortunately there has been little communication between these fields. There is also a big discrepancy between the theoretical and empirical studies. There are theoretical studies which simulates the development of division of labor by assuming a benefit in production and a high transaction cost that is lowered over time, while the empirical studies talk about the first specialists as mostly catering to spiritual needs and that the first craft specialists are attached to a leader.

2.6.1 Evolution

The first specialists were part time only, still having to provide for their own sustainment and their function was either that of a healer or an organizational leader. As the society evolves, the healer and organizational leader gains more influence and ceremonies become more important. The ceremonies requires new goods, only a few individuals are assigned, or allowed, to produce these new resources, they become part time specialists, the roles become more formalized. Most of these tasks require very little work and are not associated with basic needs, such as food and shelter. The goods are still distributed among the group without any expectation of direct reciprocity, no market exists. Some of the ceremonial items are not available locally and have to be traded for with other groups, geographical specialization and trade appears.

When the group grows, the food gathering has to be intensified. While there had been some sharing between families, the food was generally gathered by the same individual who ate it, or a close relative. Now cooperation becomes more important, there is a limit on how long from the group individuals can travel to gather food, so the area does not increase as fast as the population density and more food have to be gathered per acre. Many of the advantages of hunting in a group are due to division of labor. For example a couple of individuals could drive the prey into a trap set by others. These roles can be assigned differently for every hunt, so they are not necessarily specialized. As there is still no market, the organizational leader has an important task in assuring that everyone get some of the surplus, otherwise there would be fights and the cooperation would break down and the society would have to be divided into smaller parts.

When the group settles down and starts a village, population density grows even more and food gathering has to be intensified further. Some crafts specialists might start appearing, usually they are attached to some leader or other elite, receiving food and housing as pay for their work. The increasing specialization allow the group to accumulate more culture and utilize new technology. There is evidence that metal working is so complex that it requires a specialist. Eventually the attached specialists will break free and become independent, some groups skipped the attached specialists and received independent specialists right away. When the leader no longer have control over the specialists, they have to trade their goods for food and other resources. Specialized traders appear.

From this point and on, specialization keeps increasing, much of the new technology will require specialists, the population density increase and the society becomes more complex, which in turn requires new specialists.

2.6.2 Specialization, Technology and Population Density

It is clear that there is a complex relationship between specialization, technology and population density. Exactly how this relationship is built up is still unclear however. This is one area that has not been studied very extensively and more theoretical work is necessary. Most likely the population keeps increasing by itself and when the population density becomes high, the society either has to be divided or find more efficient ways to gather food and organize itself. First dividing labor helps with this increased efficiency, then specialists and new technology. In more advanced societies specialists are required just to uphold the current level of technological advancement.

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Chapter 3

Modeling Specialization and Division of Labor

It would be attractive to be able to formulate a single "Theory of All Specialization", corresponding to the physicists' dream of a Theory of Everything. When one starts thinking seriously about specialization, though, it soon becomes obvious that it is hopeless to vie for such a general theory. The reason for this is that the concept of specialization is too rich. As we shall see, specialization can, and must, refer to a whole plethora of varying but interrelated phenomena. Further, both causes and effects of specialization come in many different kinds.

The next insight one comes to when thinking seriously about specialization is that is not clear to what extent it is meaningful even to hope that one can formulate substantial particular theories, "Theories of Some Aspect of Specialization" of good validity. It depends on whether the aspect of specialization under study is sufficiently isolated.

In this chapter we take the most general modeling approach possible. This entails first, *identifying relevant entities and their relationships to each other*, and second, *illustrating through small examples of models* how these theoretical building blocks can be formalized and represented mathematically.

The point of this general and basic approach — which is novel, as far as we know — is to lay the groundwork for a range of model-based investigations of research questions related to specialization. We will conclude with discussing a number of such questions, some of which we will investigate later in this thesis and others that must be left to future research.

Because of the complexity and the chameleon nature of the specialization phenomenon, this chapter will discuss and model a large number of entities and relationships and the subject matter does not lend itself to structuring in any obvious way. The structure we have settled upon is to start by providing a general framework for modeling specialization and division of labor. We then continue by discussing the individual's choice on the level of specialization and then proceed to various aspects of specialization in groups. Within each section we discuss entities and relations that a theory must consider, including causal relationships where specialization either drives or is driven by some other phenomenon. The chapter is concluded with a discussion on possible future lines of research and an introduction to how the papers in this thesis fit into the framework developed in this chapter.

3.1 General Framework

This chapter covers many different aspects of specialization and a general framework will help the understanding of the entire process since we can relate each aspect of specialization to a specific part of the general framework. The most general framework for specialization possible will just need a few components. Each component represents a number of, possibly very complicated, interactions, but at this level we are not concerned with the underlying complexity. Different aspects of each component and the interactions between components will be studied in the following sections.

The first component of the general framework is the *tasks* or *fields* that are or can be performed, either by individuals or groups. We need to define a set T of possible tasks. Specific tasks in T will often be referred to by $\tau \in T$.

The *strategic choice* made by individuals or groups is the second component. This is the choice on the number of tasks in T to perform, or how to distribute time between different tasks. The strategic choice can also include a choice between performing tasks and learning how to perform new tasks or to increase ones skill in already known tasks. The allocation of time to performing a specific task τ by a group or an individual i will be denoted $\phi_{i,\tau}$ and the distribution of time across all tasks can be described by a vector $\Phi_i = (\phi_{i,A}, \phi_{i,B}, \ldots)$ for task A, B and so on. Time allocated to studying a task τ will be denoted $\psi_{i,\tau}$.

When tasks are performed they will yield some output in terms of resources or services. The production is determined by a *production function* h. The choice made by the individual on the degree of specialization as well as the resulting output of resources or services is dependent on *the current state of the world*. When thinking of which parameters are needed to describe the current state of the world it quickly becomes apparent that they are very numerous. For example, the skill of the individual, decisions made by other individuals, availability of specific technologies or tools that facilitate production of some resources, the state of the environment such as depleted resources, the efficiency of the market and so on. The extent of the specialization can also be limited by the individual's decision process. The individual's ability to make estimations of these parameters and bounded rationality as well as psychological mechanisms such as risk aversion and temporal discounting can prevent individuals from making correct decisions, causing the level of specialization to deviate from the optimal.

The number of parameters and their interactions makes defining a realistic production function impossible, or at least very hard. We will therefore use S to denote the current state of the world. S will be considered as containing any information that is relevant for the study at hand and required for describing the world in its current state. Possibly including, but not limited to, the parameters mentioned above. The production function is a function of the the amount of time allocated to the task and S and results in the possession of $p_{i,\tau}$ resources of type τ (i.e. resources produced by performing the task τ):

$$p_{i,\tau} = h_\tau(\phi_{i,\tau}, S).$$

For simplicity we can use P_i to denote the vector containing the total amount of resources available to the individual:

$$P_i = (p_{i,A}, p_{i,B}, \ldots),$$

for resources A, B and so on. P_i will be referred to as the *possession profile*.

After production, someone who has produced a significant amount of some resource may wish to *exchange* some of these resources for other resources or services on some kind of *market*. After exchange, the amount of resources of type τ possessed by an individual changes from $p_{i,\tau}$ to the final amount $p'_{i,\tau}$. The market can be described as a function of the individuals possession vector and the current state of the world. The output of the market function is the *final possession profile* P'_i:

$$P'_i = m(P_i, S),$$

where m is the market function.

The final component of the general framework for specialization and division of labor is the *utility function* w, which is a function of the final possession profile and the current state of the world:

$$w(P'_i, S).$$

The utility function includes basic needs as well as goods which are not necessary for survival. Throughout this chapter, we will assume that the utility is simply the product of each resource that can be produced. Individuals will therefore need each resource in equal amounts.

These five components, tasks, strategic choice, production function, market and utility function together with the concept of the current state of the world provides a basic framework for any study of specialization and division of labor. The models presented in this chapter will also follow the notation used in the general framework.

3.2 Individual Specialization

We begin our study of specialization at the most basic level, the individual level. Here we study the basic questions on what advantages are there to specialization at the individual level? How do these advantages materialize? And even more fundamental: what might it imply that an individual is a specialist? At the very least there are two, intimately related but distinct, potential answers based on either *behavior* or *skill*.

3.2.1 Behavioral Specialization

In terms of behavior, an individual may be a specialist in the sense that she *engages only in one, or a few, of a set of possible tasks*. A specialist in a slightly different sense is someone who *spends more time on some tasks* than on others.

To represent specialization in the first (discrete) sense, will use the set T of possible tasks, for which an individual i engages in a subset $T_i \subset T$.

The second sense is continuous, and to represent it mathematically we use the amount or proportion of time $\phi_{i,\tau}$ that individual i spend on a given task τ. In this case, the set of tasks being performed is defined as

$$T_i = \{\tau : \phi_{i,\tau} > 0\},$$

which might be the entire set T.

We can talk about different degrees of specialization at the individual level by comparing the number of tasks, $|T_i|$, performed by the individual with the number of possible tasks $|T|$. In the continuous case, we can compare the amount of time spent on each task with a uniform distribution of time across tasks:

$$\sum_{\tau \in T_i} \left| \phi_{i,\tau} - \frac{1}{|T|} \right|,$$

where a lower value indicates less specialization.

Increased efficiency in the case of behavioral specialization comes from economies of scale due to spending a longer period of time on each task and saving the time and energy spent moving between tasks. This cost is dependent on the number of different tasks an individual performs, so it is the same in both the discrete and the continuous case. If there is a cost c in moving between tasks, we have that the total cost to the individual is $c|T_i|$.

Example Utility Function

We can now use the general framework together with a few assumptions to create a more specific model. Assume that each individual have a number of basic needs or required resources (food, water, shelter, etc.). Each of these needs can be satisfied in one or more ways, each way of satisfying need j is represented by a task in a set R_j, which is a subset of T. We can now specify a basic utility function for the payoff to the individual in a single timestep

$$w(P_i', S) = \prod_{j=1}^{r} \left(\sum_{\tau \in R_j \cap T_i} p'_{i,\tau} \right) - \sum_{\tau \in T_i} c_{r,\tau}(\phi_{i,\tau}, S),$$

where $c_{r,\tau}(\phi_{i,\tau}, S)$ is the costs in resources or energy for spending $\phi_{i,\tau}$ time performing task τ when the world is in state S.

Depending on the production function h and the market, different degrees of specialization will be optimal. While we do not know the shape of h, we can still determine how different functions would influence the optimal level of specialization. First, h should typically be an increasing function, as it is the cumulative amount of produced resources from spending a certain amount of time performing some task and to perform the task if the amount of resources decrease from increased effort does not make sense. It also needs to include any setup cost for the task in terms of time. Say that some task τ is performed in a remote location that takes x hours to reach, then $h_\tau(\phi_{i,\tau}, S)$ should be ≤ 0 for $\phi_{i,\tau} < 2x$. If the function increases slower than linear, a generalist strategy will typically be best if c_r is not too large. If c_r is large, partial specialization can be more efficient. With h being a linear function, the individual should be indifferent when choosing whether to be a generalist or a specialist if there are no costs, otherwise specialization is more efficient. If h increases faster than linear, specialization always maximizes the payoff. Finally, h can be S-shaped, in which case full or partial specialization is the best strategy, depending on the exact form of h and the size of the costs.

3.2.2 Specialization in Skill

In terms of skill, a specialist is someone who has invested more in learning a specific skill than others. Increased efficiency due to skill can come from avoiding the cost of learning how to perform certain tasks, which may include time, energy or risky trial and error. It can also come from a direct increase in production due to the individuals attributes, genetic or learned, being better suited for a specific task.

The skill in performing a specific task can increase when the individual performs the task (i.e. through practice and experience). It is also possible that individuals invest in learning how to better perform a task, or learn new tasks, possibly as a reaction to a change in the environment.

When modeling specialization in skill, S needs to contain information on historic actions, the production function needs to take skill into account and the utility function needs to include learning costs. Let $\phi_{i,\tau,t}$ be the amount of time spent performing task τ at timestep t. We can now incorporate learning by doing into the model. The accumulated skill, and therefore the production function h, is dependent on the amount of time that has been spent on performing a specific or similar tasks in the past by the individual. In the simplest case, this is just some function of the sum of the time allocated to performing the specific task up to the current timestep t:

$$\sum_{j=1}^{t} \phi_{i,\tau,j}.$$

Similarly, we can include learning by studying. This means that the individuals also have the option to allocate some time, $\psi_{i,\tau,t}$, to learn how to perform, or improve their skills at performing task τ at time t. Increased skill can be manifested in several ways, it can either decrease the costs associated with performing some task, or it can be a direct increase in the output from performing the task.

In the case of specialization in skill, h is dependent on more parameters than when we just have specialization in behavior. These new parameters allow individuals to accumulate knowledge over time, which may increase their productivity. It is possible that some tasks can not be performed at all without the individual spending some time, x, learning first, i.e. $h_\tau(\phi_{i,\tau}, S) = 0$ unless $\sum_{j=1}^{t} \psi_{i,\tau,t} > x$. In this case, the behavioral repertoire that can be learned by an individual is limited by the time that can be spent learning rather than collecting resources, memory and life time. It is also a reasonable assumption that h should increase with the amount of time spent performing a task, $\sum_{j=1}^{t} \phi_{i,\tau,j}$ and the amount of time spent studying it: $\sum_{j=1}^{t} \psi_{i,\tau,j}$. This increase should generally be larger for the amount of time spent studying than the time spent performing the task as studies can be focused on the part of the task that the individual will benefit the most from learning how to perform in a more efficient manner. While many complex functions can be thought of, it is realistic to assume that the increase in productivity exhibits some decreasing returns when the individual has spent a significant amount of time on learning and performing the task. When the amount of time spent learning or performing a task increases, h may therefore increase as the logarithm for a task that is easy to learn or be s-shaped for a task that requires a significant initial investment in order to perform efficiently.

A specialized individual that is dependent on a few natural resources will be more vulnerable than a generalist. An environmental change might suddenly remove a critical resource, for which there is no substitute in the specialist's repertoire. This can be implemented as a change in S over time by some, possibly stochastic function $f : S_t \rightarrow S_{t+1}$, where S_t is the state of the world at time t. h_τ could also be dependent on the total amount of time spent performing τ in the population, to model depletion of overused resources, or regrowth when they are not frequently utilized.

Example

Following the example from the previous section, the payoff function for individual i becomes

$$w(P'_i, S) = \prod_{j=1}^{r} \left(\sum_{\tau \in R_j} p'_{i,\tau} \right) - \sum_{\tau \in T_i} c_{r,\tau}(\phi_{i,\tau}, S) - \sum_{\tau \in T} c_{l,\tau}(\psi_{i,\tau}, S),$$

where $c_{l,\tau}(\psi_{i,\tau}, S)$ is the cost for spending $\psi_{i,\tau}$ time units learning how to perform task τ.

3.2.3 Behavioral Specialization versus Specialization in Skill

In many cases, an individual knows how to perform many different tasks, but only perform a few of them, i.e. specializes in behavior but not in skill. As pointed out in the previous section, at least at a first glance, specialization in skill gives additional advantages compared to specialization in behavior. Why then, do specialization in behavior occur?

A first observation is that this does not hold to the same extent for tasks that require a longer education and that are not vital. Humans are quick learners and easily pick up how to perform simple tasks, thus some knowledge will spread in the population entirely without individual intent.

The comparative advantages due to individual differences, as well as the benefit from them, can be hard to determine in advance. Thus, the advantage of specialization might not become clear until several individuals can directly compare their efficiency in different tasks. In the other end of the spectrum, when tasks are very costly to learn, the knowledge is worth more than the potential increase in efficiency from selecting the best individual for the task after observing actual production. Therefore, this will become less common as cultural evolution progresses and introduces more complex methods of production.

Further, knowledge in several different areas might be useful to decrease the risk from dependence on others and to compensate for variations in the production. A specialist might still spend a small proportion of the time performing other tasks when needed. When the population increases, the variations in production will decrease and this becomes less important.

Learning Costs versus Comparative Advantages

To show how low learning costs can lead to specialization in a task, but not in knowledge, assume we have two different tasks yielding different resources, A and B as well as two individuals, 1 and 2. If they know how to produce the resources, individual 1 produces $(p_{1,A}, p_{1,B})$ and individual 2 $(p_{2,A}, p_{2,B})$. The cost for learning how to perform one task is c and the payoff is the amount of resource A multiplied by the amount of resource B. If they can communicate which task they intend to learn and both specialize, the expected production of each resource will be:

$$\frac{1}{2}(p_{1,A} + p_{2,A}) - c$$

and

$$\frac{1}{2}(p_{1,B} + p_{2,B}) - c$$

respectively. Assuming they divide the produced resources equally, the utility for each individual is:

$$\frac{1}{8}(p_{1,A} + p_{2,A})(p_{1,B} + p_{2,B}) - c.$$

If, on the other hand, they decide that both of them should learn both tasks the payoff for each individual will be

$$\frac{1}{4}p_{1,A}p_{2,B} - 2c,$$

assuming 1 is better at producing A and 2 is relatively better at producing B. It is then optimal for both individuals to learn both tasks whenever

$$\frac{1}{4}p_{1,A}p_{2,B} - 2c > \frac{1}{8}(p_{1,A} + p_{2,A})(p_{1,B} + p_{2,B}) - c,$$

which can be rewritten as

$$c < \frac{1}{8}\left(p_{1,A}p_{2,B} - p_{1,A}p_{1,B} - p_{1,B}p_{2,A} - p_{2,A}p_{2,B}\right),$$

where we can see that if the difference in productivity is low, the right hand side will be negative, so the inequality will hold. It is clear that it is only worth the extra cost to learn how to perform both tasks when the benefit is substantial and the cost of learning the tasks is very low.

Generalists as a Buffer for Production

It is both possible and likely that the production rate of some resource varies depending on some random factors. This means that if tasks are some intermediate step in producing a final resource, or if the utility function is dependent on production of each resource, it is possible that bottlenecks in the production appear due to randomness. If just a few individuals produce some resource and production decreases significantly due to random fluctuations in productivity, the entire production chain will suffer. This can be remedied by having a number of individuals in the population that can switch between tasks depending on the current requirements, i.e. specialists in behavior, but not in skill.

We can use a model to illustrate how the variation in production increases the value of generalists in smaller populations. Assume that there are two resources and each individual produces one of the resources in an amount given by drawing from a normal distribution with mean μ and standard deviation σ. We assume that production is equally efficient in both fields, so there is no difference in the μ parameter depending on field. If there are N_s specialists producing each of the resources, the total production of each resource is given by the normal distribution with expected mean $N_s\mu$ and standard deviation $\sqrt{N_s\sigma^2}$. The expected difference in production between the two different resources is given by

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} |x - y|\, f(x)f(y)dxdy,$$

where f is the density function of the normal distribution $N(N_s\mu, \sqrt{N_s\sigma^2})$:

$$f(x) = \frac{1}{\sqrt{2\pi N_s\sigma^2}}e^{-\frac{(x-N_s\mu)^2}{2N_s\sigma^2}}.$$

Since we are just interested in the expected difference in productivity between the two fields, the expected mean does not matter, so we can set $\mu = 0$ when plotting the graph. Figure 3.1 shows how the large the expected difference in production between the fields per specialist is depending on σ and N_s. We

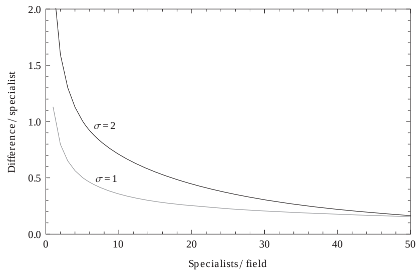

Figure 3.1: Expected difference in production with two fields, which are both required in the same amount. As the number of specialists increase, a proportionally smaller number of generalists is required to ensure that the production of both resources is equal.

can see that the difference decreases quickly at first, but then slows down considerably. Whether the difference is large or small depends on the relation between μ and σ. With 50 specialists in each field, the expected difference in total production per specialist is just above 0.15 for both $\sigma = 1$ and $\sigma = 2$. If $\mu = 1$, then there will be a difference of 15% in the total production between the fields, while if $\mu = 10$, the difference is only 1.5%. From this model we can see that see that individuals specializing only in behavior can increase the utility of the population when the variance in productivity is large in relation to the mean.

3.3 Division of Labor

While division of labor is distinct from specialization, they are closely associated. An individual can specialize in a few tasks without having a counterpart to trade with, or being a part of a group. These tasks obviously needs to include everything that is required for survival, however advantages can be had from for example limiting the number of different food sources that are utilized. When an individual does not have a market or other individuals to trade with, she is required to satisfy every basic need herself. Therefore we need

$$\forall j \exists \tau \in R_j \cap T_i$$

to be true. Further, it is required that the production of each of these resources is above some minimum requirement, m_j, to satisfy each need j, such that

$$\forall j \sum_{\tau \in R_j \cap T_i} h_\tau(\phi_{i,\tau}, S) \geq m_j.$$

Division of labor requires a group of cooperating individuals and can greatly increase the benefits from specialization but also comes with additional costs and risks. With division of labor, every individual does not need to produce every necessary resource and the production of each resource may be divided into smaller tasks performed by different individuals. Division of labor therefore greatly increases the amount of specialization possible. The group's total production can increase because individuals do not need to spend the time learning how to perform every necessary task. An individual that has attributes that makes her well suited for a specific task can spend a large proportion of her time performing that task, possibly even being the only individual performing that specific task and then trade for other resources or services. Division of labor can even give the group access to tasks or resources that can not be utilized by a single individual.

The increased production that results from avoiding learning costs and utilizing comparative advantages allows more time to be spent on activities that just increases quality of life or makes costly projects that increase future production possible. The group can then become dependent on the good intentions of a few individuals that produce critical resources. This can lead to inequality and costly conflicts. When just a few individuals know how to produce some resource, the risk for loss of culture increases.

At group level, the requirement that every individual produce resources that satisfy every need is relaxed, so that $T_i \cap R_j = \emptyset$ may be true for some combination of i and j. This allows for much more specialization and means that we can get specialization even in the case when there is just one way to satisfy a need, or different specialists that satisfy the same need by performing different tasks. Let N be the number of individuals in the group, we then need

$$\forall j \sum_{\tau \in R_j} \sum_{i=1}^{N} h_\tau\left(\phi_{i,\tau}, S\right) > N m_j,$$

which is a significantly weaker requirement than in the case without division of labor.

In a group it is also possible that some individuals specialize in providing tools or services that increase efficiency when producing other resources. Since these tools and services are not necessary to produce the resource, they have a special position in the production chain. It is desirable, but not mandatory to optimize the number and distribution of these specialists.

3.4 Market

Division of labor requires a market for exchanging the produced resources. At the most basic level this may just be exchange within the family or that individuals meet at random and can exchange resources only with others that they meet. At the other extreme we have a perfectly working market without any transaction costs and a very large population. For most societies the reality is obviously somewhere in-between these extremes, with some transaction costs and a possibly large, but limited population. The market aspect of division of labor has been modeled extensively by economists as shown in the previous chapter, but for completeness we will study two basic models of the extremes.

3.4.1 Random trading partner

If individuals can only trade with a randomly chosen trading partner in each timestep we have a very rudimentary market with a high risk of not finding a suitable trading partner. Assume that there are two tasks, A and B, which produce corresponding resources, both of which are required by individuals. Each interaction includes two individuals, 1 and 2. The distribution of time between the tasks for individual x is $\phi_{x,A}$ and $\phi_{x,B}$, which results in a production of $P_x = (p_{x,A}, p_{x,B})$ resources, where $p_{x,\tau} = h_\tau(\phi_{x,\tau}, S)$. The utility function is the amount of A resources obtained multiplied by the amount of B resources so that $w(P'_x) = p'_{x,A}p'_{x,B}$.

The exchange rate is set depending on the availability of each type of goods in the interaction:

$$r = \frac{p_{1,B} + p_{2,B}}{p_{1,A} + p_{2,A}}.$$

Putting the exchange rate into the utility function yields

$$w(P'_1) = (p_{1,A} - \delta)(p_{1,B} + \delta r)$$
$$w(P'_2) = (p_{2,A} + \delta)(p_{2,B} - \delta r),$$

where δ is the amount of A resources that individual 1 trades for δr resources of type B. To find out how much of the resources that are traded, we maximize the utility function and solve for δ

$$w(P'_1)\frac{d}{d\delta} = 0 \Rightarrow \delta = \frac{p_{1,A}p_{2,B} - p_{2,A}p_{1,B}}{2(p_{1,B} + p_{2,B})},$$

maximizing $w(P_2')$ yields the same result for t, so the individuals agree on the amount to be traded and the market clears. Inserting this back into the utility function gives the final payoff

$$w(P_1') = \left(p_{1,A} - \frac{p_{1,A}p_{2,B} - p_{2,A}p_{1,B}}{2(p_{1,B} + p_{2,B})}\right)\left(p_{1,B} + \frac{p_{1,A}p_{2,B} - p_{2,A}p_{1,B}}{2(p_{1,A} + p_{2,A})}\right)$$

$$w(P_2') = \left(p_{2,A} + \frac{p_{1,A}p_{2,B} - p_{2,A}p_{1,B}}{2(p_{1,B} + p_{2,B})}\right)\left(p_{2,B} - \frac{p_{1,A}p_{2,B} - p_{2,A}p_{1,B}}{2(p_{1,A} + p_{2,A})}\right).$$

To see what is required for a specialist strategy to invade a population where everyone is a generalist, set $\Phi_1 = (s, 0)$ (specialist which only produce A) and $\Phi_2 = (g, g)$ (generalist which produce the same amount of both goods). Let $\pi(P_x, P_y)$ be the payoff received by an individual with strategy x when interacting with an individual with strategy y. In a game where individuals are paired off at random, a new strategy y can invade a population using strategy x if $\pi(P_x, P_y) \leq \pi(P_y, P_y)$ or $\pi(P_x, P_x) < \pi(P_y, P_x)$. Since $\pi(P_2, P_x) \geq g^2$ is true for all strategies x and $\pi(P_1, P_1) = 0$, the first inequality cannot be satisfied. Specialists can then invade if and only if $\pi(P_2, P_2) < \pi(P_1, P_2)$, inserting the values yields

$$\pi(P_1, P_2) = \frac{s^2 g}{4(s + g)}.$$

We can assume $g = 1$ without loss of generality and then simplify, which gives us that specialists can invade if and only if

$$s > 2 + \sqrt{8}.$$

In this case, with only a very basic market, a specialist would have to produce about 2.4 times more than a generalist to be able to invade. Thus there needs to be a significant advantage to specializing in terms of production for specialists to appear.

3.5 Specialization on a very efficient market

If instead of meeting at random, individuals can meet at a market to exchange their resources, no one takes the risk of meeting an individual with which they cannot trade. Specialists then take a much smaller risk since they will always be able to trade if there is someone in the population to trade with.

We define q_1 as the proportion of individuals with production P_1 and q_2 as the proportion of individuals producing P_2 so that $q_1 = 1 - q_2$. Just like in the previous model, the exchange rate r, is set depending on the amount of each resource that is available on the market. In the efficient market model this means that the exchange rate is also dependent on the proportion of each strategy:

$$r = \frac{q_1 p_{1,B} + q_2 p_{2,B}}{q_1 p_{1,A} + q_2 p_{2,A}}.$$

Let δ_1 be the amount of A resources that an individual of type 1 trades for for $\delta_1 r$ B resources. Similarly $\delta_2 r$ is the amount of B resources that individuals of type 2 gives in exchange for δ_2 A resources. The utility for the individuals is therefore:

$$w(P_1') = (p_{1,A} - \delta_1)(p_{1,B} + \delta_1 r)$$
$$w(P_2') = (p_{2,A} + \delta_2)(p_{2,B} - \delta_2 r).$$

To find the amount of each resource that is traded we take the derivative and find the maximum for each type of individual

$$w(P_1')\frac{d}{d\delta_1} = 0 \Rightarrow \delta_1 = \frac{p_{1,A} r - p_{1,B}}{2r}$$

$$w(P_2')\frac{d}{d\delta_2} = 0 \Rightarrow \delta_2 = \frac{-p_{2,A} r + p_{2,B}}{2r}.$$

By inserting the expression for r and simplifying, it is possible to show that $q_1\delta_1 = q_2\delta_2$, so the market will always clear. To find in which situation we have an interior fix point, we set $w(P_1') = w_(P_2')$ and solve for q_1:

$$\left[q_1 = 1 + \frac{1}{2}\left(\frac{p_{1,A}}{-p_{1,A} + p_{2,A}} + \frac{p_{1,B}}{-p_{1,B} + p_{2,B}}\right), \quad q_1 = \frac{-p_{1,A}p_{2,B} - p_{2,A}(p_{1,B} + 2p_{2,B})}{2p_{1,A}p_{1,B} - 2p_{2,A}p_{2,B}} \right]$$

If we have a closer look at the second solution, we can see that, the nominator is negative, thus for q_1 to be positive and between 0 and 1, it has to be true that

$$-p_{1,A}p_{2,B} - p_{2,A}(p_{1,B} + 2p_{2,B}) > 2p_{1,A}p_{1,B} - 2p_{2,A}p_{2,B}.$$

But we can simplify the expression to

$$-p_{1,A}p_{2,B} - p_{2,A}p_{1,B} > 2p_{1,A}p_{1,B},$$

which can never be true since the left hand side is always less than or equal to 0 and the right hand side is always more than or equal to 0. We can conclude that this is not an interior fix point.

In order for the system to have an interior fix point, the first root has to be between 0 and 1, which means that the expression within the parentheses have to be between 0 and -2. So, we have an interior fix point if and only if:

$$-2 < \frac{p_{1,A}}{-p_{1,A} + p_{2,A}} + \frac{p_{1,B}}{-p_{1,B} + p_{2,B}} < 0 \quad (3.1)$$

Now we can see that an interior fix point can exist only if $p_{1,A} > p_{2,A}, p_{2,B} > p_{1,B}$ or $p_{2,A} > p_{1,A}, p_{1,B} > p_{2,B}$. This show that agents which are inferior or just as good in both fields will be eliminated by competition. More importantly, as we will see, equation 3.1 means that specialists can invade a population of generalists as soon as there is a slight advantage in total productivity from specializing.

Assume we have an original population of generalists, with productivity $P_2 = (g, g)$. If specialists with productivity $P_1 = (s, 0)$ were to appear in the population, then from equation 3.1 we can see that they would be able to invade if and only if:

$$-2 < \frac{s}{g - s} < 0.$$

This inequality is satisfied when $s > 2g$ i.e. as soon as specialization yields an advantage in total productivity, or when the production function profile grows faster than linearly with more time invested in performing the task.

3.6 Coordination Costs

Division of labor is an anti-coordination game where individuals want to provide resources or services that are under produced in the population. *Coordination cost* is the deviation from the optimal distribution that appears when individuals divide tasks between themselves. Coordination costs arise from over or under production of resources and from unnecessarily overlapping costs. Thus the coordination costs will be the risk that no one or too few individuals produce a certain type of resource or the cost for an institution that ensures that all critical resources are produced in adequate amounts.

Coordination costs are distinct from transaction costs in that they are not relative to the amount of resources that are traded. We can see this in the random trading partner model in section 3.4.1, where coordination costs prevents specialists from invading a generalist population unless the advantage to specialization is substantial. If an investment in learning is required to perform some task, then coordination costs will appear when more individuals than necessary decide to learn how to perform the task.

Individually rational choices, with regards to both investment in learning and how to allocate time for producing resources, can have less than optimal results on the group level. An individual might be better off specializing and producing for example luxury items for a small minority in a population, instead of specializing in producing vital resources for other parts of the population. An individual may also decide to learn how to perform additional tasks in order to decrease dependence on other individuals. All of these effects cause coordination costs to appear.

The coordination costs are an emergent feature of models on specialization and division of labor so we do not need to explicitly include them in our models and they do therefore not have a natural position in the general framework provided in section 3.1. However, we can still build a model to study how the coordination costs appear. The scale of the coordination cost due to over- or under-production depends on two parameters, the size of the market, or effective population, and the number of tasks. When the population is large in relation to the number of tasks, individuals can choose which tasks to perform on random and every task will still be performed with a high probability. When the number of tasks is large in relation to the population, randomly choosing tasks will often result in several tasks not being performed at all or by just a few individuals. Depending on how the production chain or utility function is structured, there are different ways the coordination cost will appear.

3.6.1 Least Produced Resource

If each task provides a separate resource or an essential step in producing some final resource, then the most interesting measure of the coordination costs is how many individuals will be performing the least performed task. That task will be the bottleneck in the production chain. Assume that we have a population of N individuals which can perform $|T|$ different tasks and that each of these tasks is a part of the production chain for some final resource. If every individual choose their task at random we have that the expected number of individuals performing the least performed task is

$$E(\text{least performed}) = \sum_{x_1=0}^{N} \sum_{x_2=0}^{N-x_1} \dots \sum_{x_{|T|-1}=0}^{N-\sum x_i} p\left(x_1, x_2, \dots, x_{|T|-1}, N - \sum x_i\right),$$

where $p(x_1, x_2, \dots, x_{|T|})$ is the probability of the distribution $((x_1, x_2, \dots, x_{|T|})$ of individuals across tasks appearing when individuals pick their task at random with probability $\frac{1}{|T|}$. The probability of the distribution appearing is given by the probability mass function of the multinomial distribution:

$$p(x_1, x_2, \dots, x_{|T|}) = \frac{(\sum x_i)!}{\prod x_i!} \left(\frac{1}{|T|}\right)^{\sum x_i}.$$

Dividing E(least performed) by the optimal number of individuals performing each task gives the efficiency of the random choice setting. Taking 1 minus this number gives us the proportion of the production that is lost due to coordination costs:

$$1 - \frac{|T|}{N} E(\text{least performed}). \tag{3.2}$$

In figure 3.2 we can see how the proportion of the total production that is lost due to coordination costs changes with the population size and number of tasks. The coordination cost causes a very large loss in production when the population is small compared to the number of tasks. As the population increases, the coordination costs decrease rapidly at first and then with decreasing speed. We can see that the coordination costs are still quite high when the population is large compared to the number of tasks. With a population of 50 individuals performing 3 different tasks, just over 20% of the production is lost due to lack of coordination.

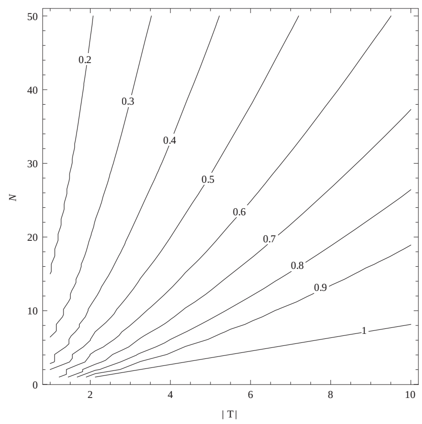

Figure 3.2: Expected proportion of the production that is lost due to coordination costs when each task is required for producing the final resource.

3.6.2 Tools and Services that Increase Efficiency

We can study a situation where there is a single resource that is needed, for example food. An individual can produce food by herself, for example by growing crops or by hunting. For the single individual working by herself, the investment in time and energy to construct complex tools, such as metal plows or advanced traps makes constructing these tools irrational or even impossible. A single specialized individual could, however, provide these tools for a large number of others. In this case, the most interesting measure of the coordination costs is the number of these efficiency increasing specializations that are not performed at all. We can calculate the expected number of tasks that are not performed at all:

$$E(\#\text{empty}) = \sum_{i=1}^{|T|-1} \sum_{j=i}^{|T|-1} r_{j-i,i} \binom{|T|}{j} \left(\frac{|T|-j}{|T|}\right)^N, \tag{3.3}$$

where $r_{j-i,i}$ are coefficients given by

$$\begin{aligned} r_{0,t} &= 1 \\ r_{n,t} &= -\left(\sum_{i=0}^{n-1} r_{i,t} \binom{t+n}{t+i} - 1\right). \end{aligned}$$

Figure 3.3 show the expected number of tasks that are not being performed

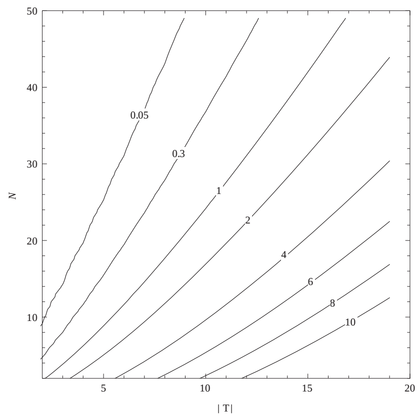

Figure 3.3: Expected number of tasks that are not performed when individuals choose task at random.

given a specific population size and number of tasks. In this case, the coordination cost decreases rapidly.

3.7 Organization

Introducing a leader can solve many of the problems that appear at the group level. Since a leader will typically not produce anything, the benefits will have to outweigh the cost of producing resources for one (or several) additional person. One of the main advantages of having a leader is decreased coordination costs. This might explain why we see powerful leaders that control almost every aspect of life in a small community, while leaders in larger communities rarely have that level of control. A leader can also decrease the inequality and conflicts within the society, but also introduces the risk of corruption, which can instead increase inequality and conflicts.

3.7.1 Organization compared to random choice

Assume that there is an institution that organizes workers in an optimal arrangement. The cost of this institution is proportional to the produced resources. For example, one person is needed as a leader for every three workers and the leader demands an equal share of the produced goods. The coordination cost would then be 25% of the produced resources.

We can take the two measures of coordination costs presented in section 3.6 and compare the coordination cost with the cost of the institution. Taking the first measure, the least produced resource, we can use equation 3.2, which gives the proportion of the production that is lost due to coordination costs. An organizational institution increases productivity if

$$1 - \frac{|T|}{N} E(\text{least performed}) > c_i,$$

where the left hand side is equation 3.2 and c_i is the proportion of the production that is used to pay the cost of the institution.

Taking the second measure for coordination costs, the number of unperformed tasks, then the increase in production in percent if the workers were perfectly organized compared to choosing at random is

$$s_p^{E(\#\text{empty})} - 1,$$

where $E(\#\text{empty})$ is given by equation 3.3 and s_p is the increase in productivity from one additional tool or service. Paying the cost for an institution is worthwhile when

$$s_p^{E(\#empty)} - 1 > c_i.$$

Figure 3.4 show how the loss due to lack of organization decreases with increasing population. An organizational institution increases total productivity when the population is small compared to the number of tasks. When the population is large enough, the loss due to lack of coordination is lower

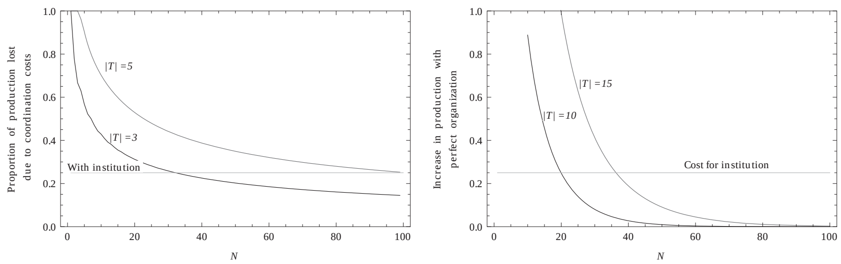

Figure 3.4: Coordination costs when individuals choose task randomly compared to the cost of an organizational institution. Left: Least produced measure. Right: Number of unperformed tasks measure, plotted with $s_p = 1.2$.

than the cost of an institution. This shows that leaders or some organizational institution may be required for specialization in smaller societies and that specialization may not be stable if that institution disappears. In a larger population however, specialization is stable even in the absence of a leader, suggesting that a decline in specialization is more uncommon in a larger population.

3.8 Demographic Transition

When modeling the transition from a population of generalists to a population of specialists, economists assume that there are several different kinds of goods that can be produced and that there are differences in skill or efficiency between individuals in the population. Exchange on some market is needed to benefit from these comparative advantages. Exchange is associated with some transaction cost, so when the cost is high only extreme differences in skill can be utilized and as the cost decreases, smaller and smaller advantages can be utilized. The transaction cost can then be assumed to decrease with increased technology and population density, resulting in a transition to more and more division of labor and specialization.

3.8.1 Model

We limit the study to just considering one type of resource. This good can be produced by generalists by themselves at some fixed efficiency. Specialists in turn can provide tools or services that are not required for the production, but increases the efficiency. This can be seen as either extending the production chain, or as letting specialists perform specific tasks within the production chain. In both cases, generalists do not perform all tasks in the population, however, they are self sufficient whereas the specialists are not.

Let the total production be:

$$P_{tot} = (N - N_s) g_p s_p^{N_s},$$

where N is the population size, N_s is the number of specialists, g_p is the basic production rate of one generalist and s_p is how much this production is increased by the presence of one specialist. Assume each individual requires 1 production unit for survival, then the total population that can be maintained is limited by $N = P_{tot}$, solving for N yields:

$$N = \frac{g_p s_p^{N_s} N_s}{g_p s_p^{N_s} - 1}.$$

If we let any surplus production be converted into new specialists, we get

$$N_s = P_{tot} - N_g,$$

where $N_g = N - N_s$ is the number of generalists. Solving for N_s gives us

$$N_s = N + \frac{ProductLog\left[-\frac{N s_p^{-N} Log(s_p)}{g_p}\right]}{Log(s_p)}$$

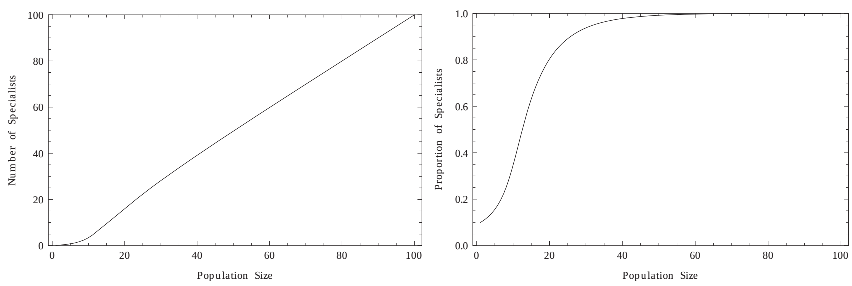

Figure 3.5: Number- and proportion of specialists in a population where all of the surplus is used to generate more specialists. $g_p = s_p = 1.1$.

If we instead choose the number of specialists by maximizing the production, by setting the derivative of P_{tot} with respect to N_s to zero and solving for N_S we get

$$N_s = N - \frac{1}{Log(s_p)}.$$

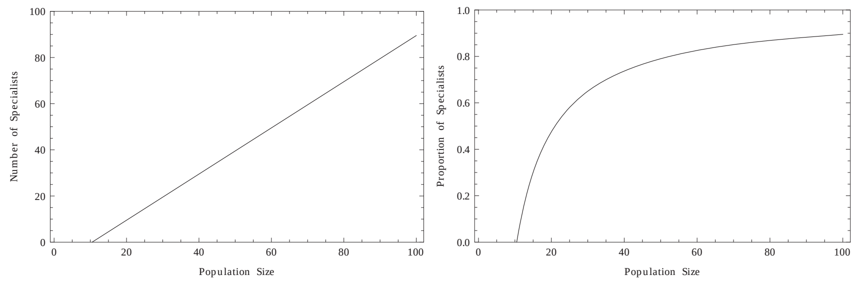

Figure 3.6: Number- and proportion of specialists in a population where the number of specialists is chosen to maximize the production. $g_p = s_p = 1.1$.

As shown by figure 3.5 and 3.6, this will result in a close to linear increase in the number of specialists with increased population. The proportion of specialists increases with a S-shaped function when the number of specialists is maximized. When maximizing production, no specialists are present in small populations. Once the population size reaches a threshold level, the proportion of specialists starts increasing. The rate of growth decreases throughout the entire interval. In both cases the proportion asymptotically approaches 1 when the population grows.

3.9 Specialization and Culture

Cultural evolution is closely tied to the value of and reasons for specializing. Cultural innovation enables new technology and allows more efficient production, possibly at the price of higher learning costs. As more complex tasks are introduced, more possibilities for specialization occur. When more knowledge is required for each task, or for the entire production chain, learning costs increase, which also increases the benefits of specialization. When the tasks becomes complex enough, it might be impossible for a single individual to perform, or even be aware of, all of them. Thus specialization becomes a requirement once the cultural evolution reaches a certain level.

3.9.1 Cumulation of Culture

Specialization can increase the amount of culture in a population. This is primarily due to three reasons. When an individual spends a large proportion of his time performing a specific task, the incentive for coming up with new, more efficient solutions increases. Since specialization increases production, more spare time is available for experimenting with novel methods of production. Third, specialization creates "experts". With a thorough understanding of a field, an expert has a higher probability of finding the areas which can most easily be improved. Innovations by an expert also has a higher probability of actually being novel to the population. When a generalist innovates, the cultural element has a higher probability of already being present elsewhere in the population, as the generalist does not have complete knowledge. Additionally, experts may be better at filtering maladaptive culture, thus increasing the proportion of useful knowledge in the population.

If individuals have limitations in time or memory, distributing culture across the population will obviously increase the carrying capacity for culture. With the increased rate of innovation this results in populations of specialists being able to maintain more culture than generalists.

Model

We can model culture as being organized in several different fields. Within each field there is a "cultural ladder", a uni-linear progression of elements. In order for an individual to reach step two of the ladder, she first has to learn step one, and so on.

Assume learning is always successful, that innovation is rare, that every individual lives for a set amount of time, l and that the age of individuals is uniformly distributed. We then have that the maximum level of culture that can be maintained per field (and will be maintained once there has been enough innovations), m, is limited by the age of the second oldest individual at the time when the oldest dies:

$$m = l - \frac{l}{N} = l\left(1 - \frac{1}{N}\right).$$

With just one field, there is no difference between generalists and specialists. Since generalists learn from every field, increasing the number of fields, f has the same result as dividing the number of learning attempts by the number of fields:

$$m_G = \frac{l}{f}\left(1 - \frac{1}{N}\right).$$

Specialists choose one field to learn from, so increasing the number of fields has the same result as dividing the population by the number of fields:

$$m_S = l\left(1 - \frac{1}{N/f}\right).$$

The total amount that can be maintained by generalists is not influenced by the number of fields. A population of specialists will initially benefit from a larger number of fields and reach the maximum total amount of culture when $f = \frac{N}{2}$, meaning that every field is studied by just two individuals. This model show that specialization can greatly increase the amount of knowledge we can maintain in a population.

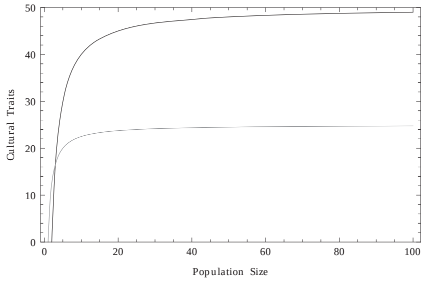

Figure 3.7: Fixed lifetime of 50 rounds, two fields. The graph shows the total amount of culture that can be maintained, per field, in a society with exclusively specialists or generalists (plotted with two fields).

3.10 Remaining Questions

This chapter gives an overview of how we can model specialization and division of labor. The simple models presented here are examples of the different interactions and processes that can be modeled. The papers in this thesis all extend the concepts presented in this chapter, but there are still many unanswered questions. This section suggests some possible future lines of research, as well as shows how the papers in this thesis fits into the larger picture.

Each section in this chapter can be extended to an entire, or even several papers. Paper I of this thesis elaborates the model on the interaction between culture and specialization. The paper finds that specialization is both a driver for cultural evolution, by increasing innovation rate, as well as an outcome in that cultural cumulation forces increasing specialization.

Paper I utilizes the model for specialization and cumulative culture organized on a type of ladder and divided across different fields presented in this chapter. Relatively few papers in cultural evolution have modeled cumulative culture, the ladder model therefore needed to be further studied. Paper II investigates which of the learning strategies commonly studied in cultural evolution would evolve in the ladder model as well as how they influence the distribution of knowledge.

One of the conclusions of paper I is that increased cultural diversity also leads to increased specialization. Typically cultural diversity increases when individuals spend more time innovating rather than learning socially. However, under certain conditions social learning can actually help increase cultural diversity. Paper II investigates under which conditions we can observe more cultural diversity, and therefore specialization, with increased social learning. Paper II finds that this is the case only when social learning is significantly more efficient than innovation.

This chapter gives little attention to the process that leads individuals to their choice on the level of specialization. This is the topic of paper IV, which studies how individuals choose their level of specialization in terms of education. This paper finds that temporal discounting has a major influence on the choice, resulting in a level of specialization that is lower than optimal for the individual. The paper also show that specialization will lead to social stratification when some individuals have access to knowledge that others do not.

3.10.1 Complex Interactions

The models presented here have only considered the direct impact of cultural knowledge, markets, organizational institutions and population size on the level of specialization and division of labor and in some cases also how specialization influences these processes. This, however, is far enough to understand the behavior of the entire system. Most of the processes considered here also interact with each other, which may amplify the effect they have on specialization or vice versa. This also causes feedback cycles, which may greatly affect the behavior of the entire system. For example, the population size is an important determinant for the level of specialization, but the population size is in turn determined by productivity and cultural knowledge, both of which are influenced by specialization.

Including interactions between the processes that specialization interacts with can yield increased understanding of both specialization and the other processes involved. Paper I studies one such system, including several of the interactions between cultural evolution, specialization, productivity and population size. In this paper the interactions included are limited to those which directly influences either culture or specialization and that have been relevant in pre-modern times.

One suggestion for future research is to study how the market appears as a function of specialization, cultural evolution and population size. As shown in this chapter, population size has a major impact on the coordination costs for specialization as well as increases demand. Culture increases the benefits of both specialization and division of labor, which in turn makes a market necessary.

3.10.2 Specialization at Group Level

Entire groups will sometimes specialize in for example exploiting just a few of the available food sources. Why is this? One explanation for this might be religious reasons, or lack of technology. However, it might also be a rational decision, especially in a smaller population. Synergy effects from cooperation within tasks cause less specialization within the group when the population is small, but can cause the entire group to specialize instead.

If a certain food source can be more efficiently exploited when a larger number of individuals cooperate, a large proportion of a small population will be required to maximize production, leaving less time for exploiting other food sources. Related, if cultural evolution has generated technology that can significantly increase production, but also extends the production chain, many individuals will be required to produce the tools and perform the different tasks in the production chain. In a small enough population focusing the group effort on one production chain will be required to maximize the benefit from the technology.

3.10.3 Structure of Production Chains

How different types of goods are produced may affect specialization. This relates to both the attributes of the tasks involved and how different intermediate products are combined to produce the final resources.

Different tasks, or elements of a production chain might have different attributes that makes them more, or less, suitable for specialized labor. Tasks that requires little effort and skill to perform are unlikely to become specialized as the coordination and transaction costs will outweigh the benefits. The same can be true for tasks that are in low demand and require little time to learn. On the other hand, complicated tasks that can not be subdivided into smaller tasks and requires a lot of experience or knowledge to perform should be taken care of by trained specialists.

Many tasks can be performed in a more efficient manner if several individuals cooperate. When hunting, several individuals might be needed to drive the animals out of their hiding places and in the direction towards traps, or other hunters. Some can not even be performed without a certain number of individuals cooperating. Such tasks will require a significantly larger population before they can be performed by specialists.

There are a number of questions regarding the production chains that are still unclear. How do the structure of the production chain affect specialization? Does it matter if each task required for producing the goods needs to be performed in a specific order or if the goods consists of a number of other items that can be produced separately? Related to this is: how is the production chain affected by new innovations? Some innovations results in entirely new tasks and products, which may affect the level of specialization in the population.

3.10.4 Ratcheting

As shown in the previous chapter, there is empirical evidence that the level of specialization is maintained even when the population size decreases drastically. The only time we can observe a significant decrease is when social institutions and the entire society collapses. This results in a ratcheting effect. Why do specialization rarely decrease? Is there an interaction with cultural cumulation, such that specialization only decrease when there is a significant loss in cultural knowledge?