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Essays on the self-organization of urban economies

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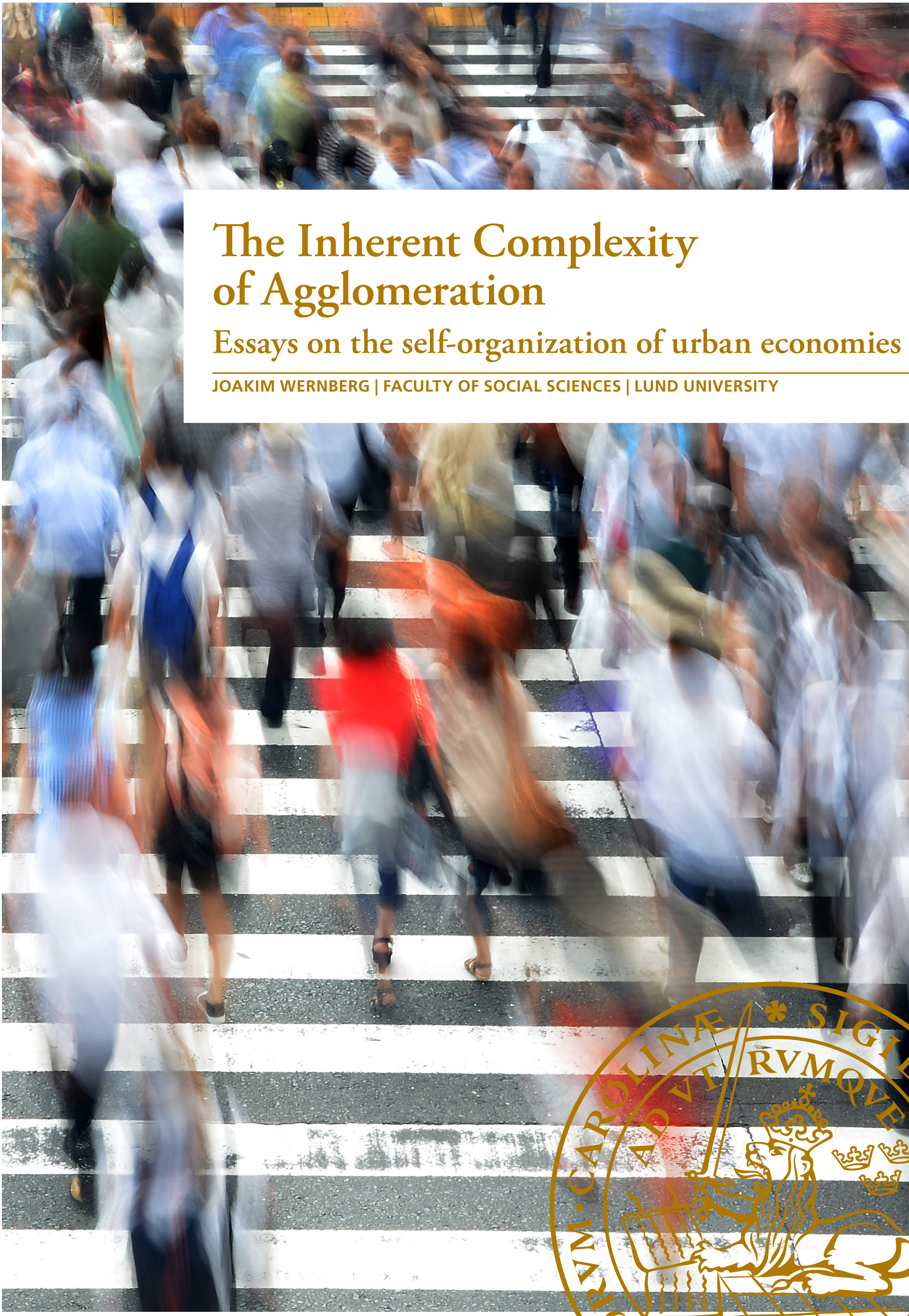

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Essays on the self-organization of urban economies

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Essays on the self-organization of urban economies

Joakim Wernberg

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This doctoral thesis combines complexity science and economic geography in order to explore bottom-up, self-organizing principles within urban economies, in particular in relation to the flow of information and knowledge between people. The thesis consists of a kappa that covers the general theoretical framework and four papers. The papers cover urban scaling and intra-urban scaling analysis, local interactions and informational spillovers , collective information processing, productivity benefits related to city size, diversity and specialization externalities, social capital and urban interactions.

Key words: Complexity, complex adaptive systems, self-organization, urban scaling, agglomeration economies, informational spillovers, micro geographies, urban growth, information flows

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Content

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All the good ideas are rooted in conversations with others, any faults are my own.

Chapter 1:
Framing the problem

1.1 Urban growth from the bottom up

Cities are a rising priority on the agenda of policy makers at all levels of government as well as academic researchers around the world. The promises of smart cities, sustainable urban innovation and vibrant startup ecosystems are contrasted by the threats of rising segregation, crime and congestion. What warrants this urgency to address urban issues is not merely the geographical concentration of people to cities, but also what's going on inside these cities. Cities showcase, for better and for worse, the interconnectedness, interdependence and entanglement that characterizes society and the economy in the wake of rapid technological development and globalization. The proximity between people and firms serves as a form of accelerator for face to face interactions, while digital technologies improves the connectivity between individuals both locally and globally. This doctoral thesis builds on and is aimed at contributing to the strand of research that explores how density enables interactions between people and the flow of information, knowledge and ideas that can promote urban productivity and growth. This is a tall order to fill, especially since neither interactions nor information flows are easily distinguishable in the buzz of urban life. If, however, such interactions were to form aggregate patterns, they would provide a footprint to follow. Therefore, I focus on studying the link between within-city variations in density externalities and productivity to complexity science and complex adaptive systems.

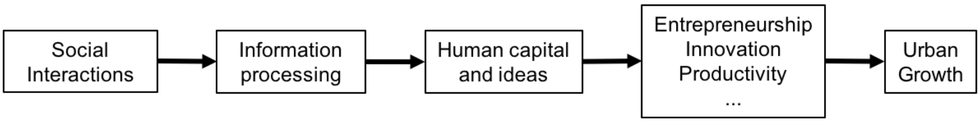
Urbanization is a fundamental shift in the economic geography that can be described by three types of changes: heterogeneity, density and scale. First, as more people move into small and large cities around the globe, the economic landscape becomes increasingly more uneven or heterogeneous, with growing concentrations of co-located people and firms. More than half of the people in the world live in urban areas (UN 2014), and cities are estimated to generate more than 80 percent of global GDP (World Bank 2017). However, this is only the face value of urbanization and cities. The share of urbanites varies considerably between countries, and in Sweden the urban population outgrew the rural roughly in 1930 (SCB 2015). Second, proximity and density challenges the social organization between people in a way that alters the way we interact. While inhabitants in a large city learn to coordinate in rush hour traffic in the subway without knowing each other, people living in small rural communities learn to know each other even if they do not actively maintain a relationship. Third, there is a significant difference between living in a city with 300 000 inhabitants compared to living in a city with 3 000 000 inhabitants. The way people connect and interact with each other changes not only with proximity but also with city size (e.g. Schläpfer et al 2014). That is, urban life changes with scale. While biological systems tend to scale so that they become slower with size (for instance, an elephant has a slower heart rate than a mouse), socioeconomic systems appear to be able to accelerate with increasing size (West 2017).

Taken together, these three changes provide a bottom-up and interaction-centered approach to urbanization and cities. "Human society can be viewed as a field which both influences the individual members of the group and is influenced by them", wrote the linguist George Kinsley Zipf when he applied his principles of least effort to what he called the economy of geography in 1949 (Zipf 2012, p. 347). Extending Zipf's metaphor, in the wake of urbanization the field of social and economic activities that constitute human society is becoming more heterogeneous and concentrated in cities, where people are exposed to each other and their interactions appear to scale with city size.

Information has always been concentrated in cities, ranging from Greek philosophers and historical records to today's knowledge-intensive and information-rich economy. An important difference is that it has become more important, and possibly also easier, to capitalize on that information. There are at least two general arguments to this point. First, as it has become easier, or at least less costly, to bring ideas and products to global markets and to grow businesses with digital platforms, the marginal worth of identifying new competitive ideas and innovation increases significantly as firms struggle not to be outcompeted. This argument speaks to the value of human capital and tacit knowledge in promoting economic growth (Gennaioli et al 2012). The second argument relates to sustainability issues. The ongoing open-ended growth that modern economies have come to depend on require more than exponentially increasing supplies of energy and resources and can only be sustained by increasingly faster cycles of paradigmatic innovations (West 2017, p. 412-426).

The conceptual approach taken in this thesis is that urban growth can be understood at least partially as a bottom-up process driven by interactions between people (Figure 1). Social non-market interactions among individuals facilitate the exchange and flow of information, or information processing, which in turn promotes knowledge and human capital in a wide sense as well as new ideas. These in turn fuel activities like entrepreneurship, innovation, productivity-increasing measures, and those activities that are successful contribute to economic growth. This type of approach belongs to the family of theories focused on agglomeration economies and endogenous growth developed during the last decades (Karlsson et al 2015, p. 9-10).

FIGURE 1: Bottom-up urban growth



Comment: This is the common conceptual bottom-up approach to urban growth taken in this thesis, based on how localized within-city agglomeration externalities and informational spillovers can spur productivity and by extension growth.

In other words, the core assumption of the approach I adopt is that information processing between individuals is a key driver to urban growth, and in particular the productivity benefits found to coincide with rising city size. This information processing is not internal to firms. Therefore, firms are not automatically presumed to be the basic element of these interactions, individuals are. From this perspective, one may argue that information processing within firms are treated as a restricted subset of all the nonmarket interactions going on within a city.

Putting interactions and the flow of information between individuals at center stage allows for a bottom-up perspective on the relation between city size and urban growth. Empirical regularities suggest that workers and firms in a large city are on average more productive than those in a small town (e.g. Combes et al 2008; 2012; Glaeser and Maré 2001; Bettencourt et al 2007; Andersson et al 2014). This can be attributed to different forms of agglomeration externalities that generate informational spillovers which in turn promote productivity benefits (Duranton and Puga 2004; Carlino and Kerr 2014). Put differently and a bit more crudely, people pick up knowledge and skills by observing, imitating and talking to each other (Roca and Puga 2017). Provided that these effects grow with city size, people would seem to benefit more from such externalities in larger cities. At the same time, a considerable increase in the number of people around as well as the number of potential interactions and meetings, not to mention the amount of information these people relate to through external links and sources outside the city, may also make it harder to benefit from externalities, or at least to increase such benefits. The signal to noise ratio rises with the number of other interactions going on around each potential externality. If externalities and productivity gains were the simple outcome of everyone interacting with everyone else, then there should be a fairly modest cap on the increasing returns to city size, but that does not appear to be the case. This observation calls for a closer scrutiny of how interactions and externalities may be internally organized to leverage city size.

There is a wide variety of other economic geographic models explaining urban growth by focusing largely on firms and industries as drivers of globalization and a flat world economy, digitization and an increasingly knowledge-intensive economy, or a rising service economy (for an overview, see Storper 1997, p 221-244). This thesis is not intended as an exhaustive model of urban growth, but rather an attempt to analyze the internal structure and organizational principles of cities in order to shed some new light on the increasing returns to size associated with agglomeration economies.

Why does this matter? Is it not good enough to know that larger cities are more productive? Whatever the internal organization of a city looks like, both individuals and firms within that city will have potential access to the whole of the city, and so are not limited to parts of it. While this is true, understanding the internal patterns and organizational principles that make up urban economies is relevant for several reasons. It matters for the location of firms within cities, for the implementation and targeting of policy initiatives to promote or prevent externalities, and perhaps even more so to understand how growing or shrinking cities can adapt to changing conditions. It also matters for improved comparisons between cities of equal size and for the identification of what makes for local exceptionality or failure. In short, it matters because just as large cities can fail, small cities can succeed in relation to what is expected from their sizes. Form a more philosophical point of view, it matters because people around the world are increasingly urbanized, and understanding more about why and how we co-locate and co-exist in small and large cities can tell us a lot about ourselves.

I make three fundamental assumptions when addressing these issues: (1) Cities can be conceptualized as systems of interdependent local social interactions, (2) these systems are complex adaptive systems, and (3) the interactions are anchored in places in the within-city geography. This results in a model of cities as complex adaptive systems of interactions anchored in social and physical space within cities.

Each of these assumptions is presented in one of the following sections in this chapter.

The purpose of Chapter 1 is threefold. First, to introduce the modelling assumptions that underpin the thesis. This is a warm-up to the more detailed and rigorous account of the research literatures and the analytical framework is then provided in Chapter 3. Second, the introduction relates the thesis to other lines of research and conceptual models of the city. This helps to put the contributions made here into a wider context.Thirdly, Chapter 1 concludes by presenting the aim, contribution and research questions that make up the thesis.

The rest of the thesis is organized as follows. Chapter 2 presents an overview and discussion about the methodological approach taken in the research. It is especially concerned with the role of theory and correlation in analyzing complex adaptive systems. Chapter 3 contains a review of the research literature by linking together and discussing density and agglomeration economies, the internal order of cities, informational spillovers and interactions, evolutionary economic geography, and finally complexity and complex adaptive systems. Chapter 3 concludes with a summary of the papers included in the thesis and a "coarse-grained" theory about complex adaptive systems in agglomeration economies. Chapter 4 provides a discussion about future research and policy implications. Finally, the four papers conclude the thesis in chapters 5-8.

1.2 Size, scale and local interactions

The way in which cities concentrate people and activities are not the same. In fact, the share of jobs, especially in knowledge-intensive services, in a region will on average tend to be more concentrated to the most densely populated places than what population in itself is (Johansson and Klaesson 2011). This suggests that there is a qualitative difference between densely and sparsely populated places. That is, a large city is not merely the linear combination of two rural towns with half the population size. It follows that the size of a city has implications for its social and economic characteristics and outputs. This is illustrated by a body of empirical regularities indicating that firms and workers in larger cities are more productive than their peers in smaller cities (e.g. Combes et al 2012). In addition, Roca and Puga (2017) find that individuals who move to large cities appear to learn skills making them more productive even after they leave the city.

Size has had, and continues to have, a central role in the scientific inquiry about cities. Batty (2015a) summarizes some ideal city sizes advocated by thinkers throughout history, ranging from Plato who put the limit at 5040, paraphrased by Mumford (1961) as the number of individuals who could be addressed by a single voice, to Le Corbusier who proposed 3 million as an ideal population size for his "city of tomorrow". Alonso (1971) pioneered a more functional approach to the ideal city size, defined as the difference between the economic gains accrued and the cost of living there.[1] This difference could then be optimized mathematically.[2] There are several caveats to the idea of determining or planning for an optimal city, including defining the boundaries of the city, controlling its size and relating to its growth trajectory. As Batty (2015a, p. 573) concludes, the ambition to optimize city size is "largely wrong-headed" as cities grow and thus pass several different sizes at which they may express very different qualities. When size is explicitly or implicitly made to be the sole determinant of function, it explains neither the variation in size between cities nor the variation in function across cities of similar size.

One way of putting the question about size into perspective is to look at the distribution of city sizes. If size, and in particular one specific size, was the dominant factor in determining the success or failure of cities, for better or worse, then we should expect some form of convergence in the distribution of city sizes both locally, nationally and globally. Instead, it turns out there are two broad regularities following the so called Zipf's law for how cities relate to each other in terms of size (Batty 2013). First, the simple form rank-size rule suggests that population is exponentially distributed across cities within an urban system. For instance, in Sweden the second largest city is roughly 1/2 the size of the largest city Stockholm, while the third largest city Malmö is roughly 1/3 the size of Stockholm. Second, the occurrence of cities of a certain type decreases exponentially with city size so that there are many small towns but very few of the largest cities. This relation suggests that as megacities emerge, there will be significantly fewer of them, then there are in the group of the currently largest cities. Batty (2015b) uses the primacy of the largest city – its relation to the second largest city – to show that between the years 1950 and 2010 the dominant position of the largest cities in the distribution appears to weaken as more people move to cities. This, Batty argues, suggests that in a completely urbanized world most cities will be small rather than large and that by extension most people will not be living in megacities but in small towns.

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[1] Not unlike the balance between agglomeration economies and diseconomies that is thought of as centripetal and centrifugal "forces" in the agglomeration economies literature today.

[2] This implies not only that the difference is positive but also that it is not strictly increasing with cost.

Still, size appears to play more than a cumulative role in the social and economic life of a city and its output. This merits a shift in focus away from *what* size a city is or should be towards *how* size relates to economic and social output across cities of different sizes. Put differently, is there a quantifiable pattern between size and economic performance in cities?

A growing body of studies advanced originally by researchers at the Santa Fe Institute in the U.S. (West 2017) and CASA in the U.K. (Batty 2013) are aimed at identifying predictable patterns between cities and their population size. In other words, they study the scaling of cities and their economies. One of the main findings from this research suggests that there are two types of such relationships – *sublinear* and *superlinear* scaling. Infrastructure and shared utilities scale sublinearly with population size, implying that when a city grows the share of transport infrastructure per capita decreases as it can be utilized more efficiently. Output from social and economic activities on the other hand scale superlinearly with population size, meaning that as city size grows linearly the economic output grows exponentially (e.g. Bettencourt et al 2007).[3]

These scaling results are consistent with the idea that cities are engines for growth and innovation, but also say something about the way cities grow. Just as a densely populated city is not merely equivalent to the aggregated sum of activities spread out in a larger rural area, cities appear to go through qualitative changes as they move from one size to another that leave a quantitative footprint. Most large cities have at some point in time been small cities, meaning there is a trajectory of growth that includes both these qualitative changes and their history, giving cities at once similarity with other cities of the same size and a unique locality based on their own past. Batty (2015a, p. 573) calls for research into these qualitative differences and how they change, for better or worse, as cities grow. This in turns prompts us to look not only at the size of cities but at their internal configuration and workings.

Empirical quantitative studies of cities in economic geography as well as regional and urban economics have for a long time tended to focus on comparing aggregate measures of cities, putting emphasis on their size but effectively making their internal workings more of a black box (Rosenthal and Strange 2004). This is equally true for urban scaling analysis, which has primarily been concerned with inter-city comparisons. Even so, both strains of research rely on a theoretical foundation that

[3] Yet other quantities, like food consumption, tend to scale linearly with population size, indicating that this measure is not affected by context and surroundings in the way that infrastructure or productivity appears to be.

associates these effects of size and scale to *agglomeration economies*, i.e. external economies of scale. These agglomeration effects are in turn attributed to micro-foundations that to a large degree originate from and condition interactions between people, e.g. sharing, matching and learning as proposed by Duranton and Puga (2004). Many of these interactions are non-market interactions that occur outside the coordination of the price mechanism, but they are still considered vital in creating and propagating informational externalities that promote the generation and flow of ideas, knowledge and information that generate *endogenous growth* (Romer 1986, Lucas 1988, Glaeser 1994).

The nonlinear character of the relationship between size and socioeconomic output, the superlinear scaling relation, suggests two things: First, that the internal structure and organizational principles related to social and economic activities within the city play a significant role in its aggregated output, and second that this internal structure changes in some manner with increasing size. West (2017) observes that when people come together in dense cities their social universe expands exponentially. The number of potential pairwise interactions between people scales as the square of the population.[4] Put differently, as the economic geography contracts linearly, social networks expand exponentially. However, it is not reasonable to assume that the scaling relation derives from individuals realizing a constant share of their potential interactions in the same manner regardless of city size. If this was the case, people in cities with more than one million inhabitants would not have time to eat or sleep. It is against this backdrop that I have framed my thesis research to study what is going on inside cities, beyond both size and scale of the whole.

Recent empirical findings along this vein, based on new disaggregated and geo-coded data, show significant within-city variations in productivity-related measures with respect to employment density (Rosenthal and Strange 2008, Andersson et al 2014, Larsson 2014). One study by Arzaghi and Henderson (2008) focuses specifically on advertising firms on Madison Avenue in New York City. The authors find productivity benefits that dissipate within 750 meters. Provided that these result derive from interactions between individuals, the results speak to the localized nature of some types of interactions and externalities. Storper (2013, p. 156-157) refers to such local interactions and their corresponding interaction structure as a "dark matter" that complements observable institutions and resources in explaining differences between similar economies and "the genius of the city" – that is, why

[4] More precisely, the number of pairwise interactions grows as the number of people multiplied by the number of people minus one, and divided by two, but it scales as the square of the population.

one city can excel within a certain niche of the economy while this success may prove hard or impossible to imitate even when the observable differences are small.

It is both theoretically anticipated and empirically demonstrated that cities are highly heterogeneous in terms of social and economic activities as well as the productivity benefits generated by these activities. This is also resonates with how people generally relate to cities. Cities like London, Paris or San Francisco, but also Lisbon, Stockholm or Tallinn each have different neighborhoods geared towards different activities – a theatre district, a financial district, a busy central business district, a Chinatown or Little Italy, a party street, an "old town" or a hip startup coffee shop. By inspection cities are essentially clusters of clusters of activity co-located in space. Batty (2013) describes cities as overlapping subsystems of interactions, a description that also takes into account that the same location within a city can be utilized by several different types of interactions.

The assumption that cities are highly heterogeneous and that size approximates their aggregate output is sufficient when comparing cities of different size to each other, but it is a crude one when it comes to understanding the internal workings of a city and, by extension, what a city really is – not in comparison to other cities but in terms of a more deep-rooted question in the social and economic behavior of humanity. Why do we seem to be drawn to cities? Why are we more productive when we live close together? Why are people increasingly prepared to pay higher rents to live cramped together in high-rise buildings? This type of inquiries prompt another approach, one that takes into account the "black matter" that gives it its locality and uniqueness – its local interactions and how they are organized.

Against this backdrop, I develop and empirically examine a conceptual model of cities that departs from local interactions with the aim to provide a better understanding of how they may influence and stimulate agglomeration economies and consequently productivity and urban growth. Every scientific investigation requires a model – a simplification of the world that is being investigated. Such a model will keep some features to scrutinize, while leaving others out entirely. In this case, that model consists of a system of local social interactions between the people that make up the city. I use the term social interactions or local interactions to describe what economists may refer to as nonmarket interactions between individuals, i.e. interactions between individuals that are not guided by prices and markets.

At the heart of this modelling approach is the assumption that interactions generate localized agglomeration externalities or informational spillovers, i.e. a form of collective processing of information or social learning between individuals (Marshall 1890; Jacobs 1970; Lucas 1988; Jones and Romer 2010; Neffke 2009). This information processing in turn promotes the transfer and generation of knowledge and ideas among individuals. This knowledge and these ideas enable people to become more productive, entrepreneurial or innovative, which for the successful cases leads to economic growth in the long run. This means that what we are really interested in, the system of interactions and the informational spillovers they generate, is rather a precursor to urban growth than a direct measure of urban growth.

Local interactions will to some degree reflect the constraints of the built environment in the city, the organizational forms of firms as well as the limitations set by formal and informal institutions. The difference is that instead of setting all these limitations first, and expecting interactions to follow from them, I make the assumptions that interactions make up a system that is worth studying in its own right, that it is significant to the social and economic output of the city and, more importantly, that it does not simply follow from the size, built environment, firms and institutions of the city. Such interactions are distributed in time and space, and it is this distribution that makes up the physical geography of the city. Along this vein, Batty (2013, p. 8) argues that locations within a city are important, but only as places that anchor interactions.

In addition, local interactions depend not only on the constraints of the local context but also on each other - they are interdependent. What I aim to capture, is simply the “black matter” problem portrayed by Storper (2013). I do this by starting with what the black matter – local interactions and their organization – might look like, what kind of patterns it may give rise to and how it may work. In summary, my simplification of the world that I wish to study is to approximate a city with a system of social and interdependent interactions through which information is transmitted, knowledge is shared, ideas are ignited and spread.

Although cities could arguably be said to be one of the most controlled and regulated geographic units imaginable in terms of its built environment public spaces and regulations, it is at the same time one of the least limited in terms of interaction potential. In other words, while there is a considerable amount of top-down control being exercised in cities, there is an at least equally important degree of bottom-up organization driven by interactions between people. West (2017, p. 29) concludes that the underlying patterns of urban scaling analysis at least to some relevant degree transcend regulatory differences between cities:

"Despite their amazing diversity and complexity around the globe, and despite localized urban planning, cities manifest a surprising coarse-grained simplicity, regularity, and predictability."

To illustrate this, think about traffic rules. In most countries, a driver needs to pass a test in order to get a driver's license. The implicit assumption is that drivers always abide by all rules. If this was the case, car horns would be a much more exotic sound in large cities than it is. In reality, car traffic, especially in large cities, tends to be a mix of formal and informal regulations. The latter refers to unwritten rules or conventions that individuals abide that and which facilitate coordination with other drivers. Traffic is a combination of top-down regulation and bottom-up organization. It is also telling that crime, which relies on individual interactions and actions, have been found to scale superlinearly with city size (Bettencourt et al 2007). This implies that that the larger the city is, the more activities there are that move outside current regulation simply by breaking laws and rules. If individual interactions were more restricted due to regulation, crime would be less likely to concentrate disproportionately in cities (Glaeser et al 1996).

In some sense, the same could be said for innovation and entrepreneurship that is aimed at introducing new things that have yet to be regulated or which may even attempt to circumvent regulation in different ways (Elert and Henreksson 2016; Elert et al 2016). For instance, companies like Uber rely solely on cities for their ride-hailing business model to gain a critical level of supply and demand, even though they have been contested and accused of operating outside of existing regulation in several cities. A city can simultaneously be both highly regulated and highly affected by bottom-up organization of local interactions.

1.3 The complex adaptive city

All models need a modelling language, i.e. a theoretical framework to position the model within. In this thesis, complex adaptive systems provides that framework. It should be said from the start, that there are many different definitions of complexity and complex systems, ranging from purely metaphorical uses to mathematical models and agent-based computer models. I will focus on the quantifiable notion of complexity, with the aim of investigating the system properties and patterns it generates within cities.

Thinking of cities as social interaction systems makes them highly apt to describe and model as complex adaptive systems (Rose 2016; Hollis 2013; Batty 2013; Bettencourt and West 2010; West 2017). Complex systems are systems that consist of basic elements, in this case individuals, that interact interdependently. That is, individuals are affected by their interactions with others, but also by the aggregate behavior of the entire system. The system is said to be adaptive if the elements can change their behavioral strategy to react to changes in their environment (Miller and Page 2007; Page 2011, Holland 2014; Hollis 2015). It should be emphasized that the system as such does not adapt – the adaptation is the outcome of reactions and changes among the basic elements. The system's aggregate behavior is thus the outcome of a multitude of interdependent individual decisions and interactions that are organized bottom-up. It follows from this adaptability to external change that complex adaptive systems are by definition evolutionary in that they change in response to their environment, or rather that their interacting elements co-evolve and contribute to a macro-level evolutionary process. This thesis will only deal with systems that are *both* complex and adaptive.

In contrast to equilibrium models commonly employed in economics and quantitative economic geography, complex adaptive systems are defined as open far-from-equilibrium or disequilibrium systems that are governed by positive feedback (Batty 2017). The openness of the system means that it exchanges energy and information with the outside world. In the case of cities this is a very important condition. Cities are not isolated from each other or from their surroundings. On the contrary, many cities act as gateways between the region they are located in and global connections to the rest of the world. In their regions they act as a hub for the local labor market as well as for the consumption of things like products, services, culture, and entertainment (Glaeser 2001a). At the same time, larger cities accumulate the necessary demand to sustain international travel and connections to cities in other parts of the world.

From a more theoretical perspective, cities are open systems because they depend on the inflow energy and information to maintain their existence. This is true for physical quantities like air, electrical power, or water that make up a city's material metabolism, but it is also true from a social and economical point of view. A city's ability to attract new people or spur new ideas and innovations is not created in a vacuum within the city. Instead, cities depend heavily on external connections both in form of infrastructure links and social ties that allow energy and information to pass in and out of the city.

The far-from-equilibrium condition is essentially a consequence of building the model bottom-up based on a variety of individual but interdependent actions and interactions. An equilibrium model is designed to seek out an optimal solution provided that all actors in the system share full information about the system. In a complex adaptive system the model is designed bottom-up reflecting that each actor has only partial information and that optimization may have to occur on a rugged rather than a smooth landscape, echoing Hayek's (1945) *information problem* and also the notion of *bounded rationality* which lies at the core of the study of complex social systems (Simon 1997; Gigerenzer and Selten 2002). This does not mean that a complex adaptive system cannot be in equilibrium, but that it is an exception rather than the rule that they are. To illustrate the difference, Miller (2015, p. 34-41) uses the case of price formation and proposes a simple bazaar model in which traders interact pair-wise with each other and randomly propose prices that are accepted if both parties benefit from them. The results match the outcome of the corresponding competitive equilibrium model, in which all traders share information and derive a fixed price, with a one third probability. In the other cases the outcome is different and earns a lower total profit. It is tempting to think of the bazaar model as suboptimal to the competitive equilibrium model, but there are at least two reasons why this may not be the case. First, it is a question of what is being optimized. The competitive equilibrium model optimizes the collective outcome without taking into consideration the individual actions, while the bazaar model optimizes each individuals actions given the situations she or he is faced with. If we wish to model a market place, or for that matter a city, it is not trivial to remove these individual decisions from the equation. Zooming out, the individual decisions and the patterns they give rise to provide a trajectory over time that contributes to the historical development and evolution of the city as well as its locality – its "black mass" to again echo Storper's (2013) description of local interactions and their structure. Second, the optimal outcome from the competitive equilibrium model may not reflect a realizable outcome, precisely because it requires everyone to act similarly on the same information. On a more philosophical note, we might argue that the difference in total profit between the two models is the price we put on being human with all that it entails. The fact that complex adaptive systems are in disequilibrium is important but risks being exaggerated. In reality, many equilibrium models are designed with the expressed awareness that real cities never reach a competitive equilibrium and the assumption that it is a good enough approximation of what is being modelled. On the other hand, some times it is not.

The difference between negative and positive feedback is simple at face value, but implies considerable differences when applied to a system. If a city is considered to be governed by negative feedback, this suggests that it will react to external forces and changes by shifting back to its resting state – the feedback is what keeps the system in equilibrium. If on the other hand, the system experiences positive feedback, an initial change or external influence may be amplified into a spiraling effect that pushes the system further in the direction of change, or in another direction entirely. Holland (2014, p. 13) describes positive feedback as the *recirculation* of signals within a system. A good example to illustrate this is viral content on the internet. As more people spread the content, it reaches a larger potential audience and is spread even further. In a similar manner, a club or a restaurant in a city may become more popular simply because it is already popular, or in the case of Arzaghi and Henderson's (2008) study on Madison Avenue mentioned earlier, a specific block may become an attractor of advertising firms and talents that contribute to positive knowledge spillovers.

These three characteristics – openness, disequilibrium and positive feedback – are also linked together. An open system that experiences positive feedback is unlikely to remain in equilibrium. What is especially interesting when it comes to cities is how social networks and physical places interact in shaping both interactions like those in the bazaar model and positive feedback effects that make a lot o people associate Madison Avenue to advertising even though they have never been there or worked in advertising.

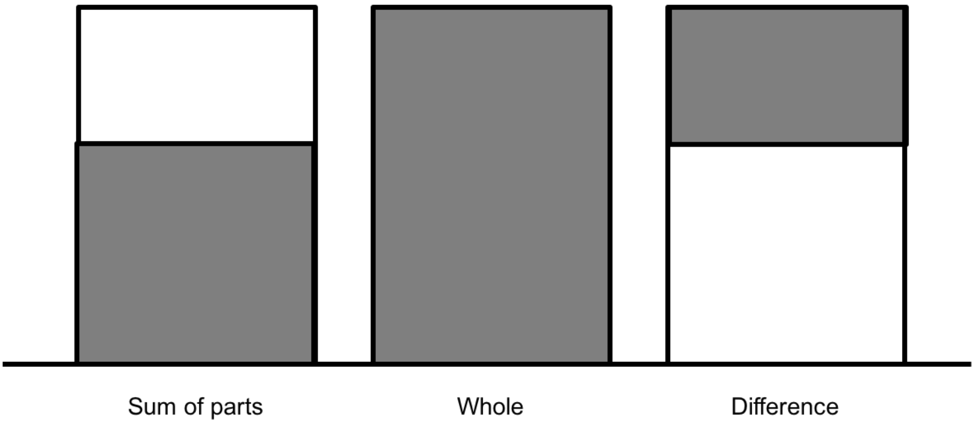
The unit of analysis in complex adaptive systems is not the individual agents or elements, but the macro-level system properties and patterns they give rise to. In particular, complex adaptive systems exhibit two such patterns that are of special interest to this thesis: *emergence* and *self-organization*. Emergence is a term used to describe properties that arise from the aggregation of parts and their interactions, but whose behavior is to some degree separated from the individual behaviors of these parts. It is best illustrated by examples from the natural sciences, like how atoms form molecules that behave differently from the atoms that they are made up of. However, it can also be employed in social systems to describe for instance a local culture or a set of local norms and values that derive from but is not exclusively dependent on the exact sum and configuration of individuals in that community. Holland (2014, p. 113-114) describes emergence as a form of organization of elements that is constrained by rules of combination derived from the level of the individual elements. This implies that the emergent phenomenon can be reduced to its parts, but it may in turn loose some of its properties. Holland illustrates it in the following way:

> *"It makes no sense to talk of the wetness of an atom, but atoms combined into collections of molecules can exhibit the aggregate phenomenon we call wetness. Similarly, the production of sound becomes spoken language only at a high level of neural and muscular organization"*

One such property that is closely associated with the study of complex adaptive systems is self-similarity, or its weaker form self-affinity, which gives rise to fractal patterns. Self-similarity describes how a specific pattern or behavior is repeated or reproduces proportionately across scales of measurement within the system. The most familiar example is of course geometrical fractals (Mandelbrot 1983), but could just as well be used to describe the economic or social activities within cities of different sizes as it is in urban scaling analysis (West 2017). Self-similarity is a hallmark characteristic of *self-organization*, i.e. patterns of organization that are derived bottom-up rather than enforces top-down. For example, think of a busy street in a large city in morning rush hour traffic: Pedestrians, bicyclists, cars, busses and trams are passing by each other, forming lines, cutting in line or forming queues to a coffee shop on the corner. At face value it may look random, but it is not. Neither is completely ordered, if it was it could be made to run much more smoothly. Instead every person has a plan, a way in which she wants to organize her own situation and surroundings, and all these plans matched together form a self-organized system. In a way, this is the very heart and soul of every large enough city where everyone does not know everyone else – people try to organize their own day-to-day lives while also coordinating with thousands of others, some of which they know and others who are complete strangers. Together they make up what Jane Jacobs famously described as a "sidewalk ballet" (Jacobs 2016). Self-organization is not, however, the same as self-regulation. As mentioned previously, cities may at one be highly regulated, and highly self-organized through bottom-up processes.

These complex adaptive system properties are also suggested by the phrase "the whole is larger than the sum of the parts". In reality, a better phrasing is that the whole is *different* from the sum of the parts (Anderson 1972). To illustrate this, consider a simple graph with three bars of equal height and width (Figure 2). The leftmost bar represents the explanation derived from studying the parts in isolation and then using the results to reconstruct the whole. This is, simplified, a typical strategy for quantitative and econometric analysis in economic geography and related fields of science. The goal of the analysis is to determine the size of an effect and its explanatory coverage. This type of analysis has the benefit that the resulting model can be used to make detailed predictions based on the micro-level mechanisms which can then be tested and verified against other empirical data– a doubling of X should be expected to generate a 2 percent increase in Y. The middle bar represents how the whole of the system behaves without trying to tease out specific causal relationships at the micro-level. To be clear, the *whole* here refers to the attempt to capture the entire system's behavior and not some ability to exhaustively and definitively capture the entire richness of the city. This is the primary contribution of a complex adaptive system analysis. The important thing is that if we wish to understand cities better, we need both the micro-level causal relationships and the behavior of the system as a whole. This is what makes the rightmost bar interesting. It represents the difference between the reductionist and the complex approach, and what links them together.

FIGURE 2: The whole is different from the sum of the parts



Comment: The phrasing that the whole is larger than the sum of the parts might be misleading. It is better to think of them as different in the sense that studying the whole and the sum of the parts may yield very different results and insights. In addition, this also allows for a comparison between the two, i.e. The difference between the whole and the sum of the parts.

Understanding this difference between the whole and the sum of its parts lies at the heart of this thesis. This is why I adopt the perspective of the city as a system of interdependent local social interactions, because it allows me to link agglomeration externalities and informational spillovers to macro-level patterns associated with complex adaptive systems.

The benefit and the drawback of complex adaptive system models is that the focus is shifted towards the aggregated system properties, rather than reducing the system to isolated parts and attempt to explain the outcome of the whole (Miller 2015). This creates a different and complementary perspective on the object of study, and provides what Holland (2014, p. 10) refers to as a formal theoretical "where to look" guidance. Holland emphasizes that this kind of approach does not produce specific predictions, but rather the opportunity to identify and investigate mechanisms that underpin phenomena like emergence and self-organization. To borrow an example from his argument, weather predictions used to rely on statistical trend analysis based on overall conditions but was greatly improved when data analysis was focused to study fronts. In the same manner, complex adaptive system analysis can contribute to identifying relevant mechanisms in the social and economic life of a city – the fronts of its local interaction structures if you will. In line with this, complex adaptive system analysis should not be thought of as an alternative to other scientific approaches to study cities, but as a complement.

1.1 Economic geography and complexity

What makes a city a city is not only the social interactions and their corresponding networks, but also that they are co-located in space. Thus, the modelling approach must be supplemented by conditions and constraints that place interactions into a geographic context. There are far more ways to approach cities within the subject of economic geography than can be covered by the scope of a single thesis, which calls for some strict demarcations. The analyses presented here are limited to the internal geography of cities and their functional regions. That is, I focus on the geography in which the system of local interactions is anchored. From this starting point, I explore questions related to cities' internal spatial organization, what happens as a city grows or shrinks, or how their internal workings relate to their aggregate output and performance. This section deals with heterogeneity, or unevenness, in interactions, space and place.

Economic geography is fundamentally a social science concerned with the spatial *unevenness* in social and economic activities. Clark, Feldman and Gertler (2000, p. 4) state in the opening of the Oxford Handbook in Economic Geography that "[d]ifference, differentiation and heterogeneity characterize the economic landscape, and are part and parcel of the intellectual agenda motivating the field of economic geography". Difference refers here to disparities between places that give rise to geographical patterns in economic activities and performance, differentiation adds the processes historical developments that lead to and sustain these differences, and heterogeneity reflects the variation in individual and aggregated characteristics that can separate two seemingly similar places. For the purpose of this thesis, it is enough to conclude that all of these categories represent heterogeneities or unevenness in the economic geography.

The study of unevenness provides a fundamental link to *entropy*, and by extension to complexity science. Entropy acts as a measure of order within a system (Wilson 2011), meaning the larger the unevenness the lower the entropy. In the physical sciences, entropy indicates a tendency towards low-energy configurations, which in a gas of particles is equivalent to a homogenous and even distribution. Concentrations, i.e. unevenness or heterogeneity, costs more in terms of energy and represent lower entropy. This is what underpins the second law of thermodynamics: For an isolated system, disorder and entropy can only increase over time, meaning that in a container filled with a gas, particles will tend towards an even distribution of random interactions. This also implies that on an astronomical time scale the universe will eventually dissolve into a even distribution of its basic elements. Entropy does not, however, increase uniformly across the board. Our planet, our bodies and our cities are all examples of local pockets of decreased and decreasing entropy (Wiener 1954; Hidalgo 2015). These local pockets must act as open systems towards their surroundings to sustain their state, which ties back to the complex adaptive systems approach to cities.

Entropy on its own may not appear very interesting to the subject of geography, but its absence is all the more intriguing. Because heterogeneity costs more energy to sustain, any concentration, unevenness or pattern represents not only a lower degree of entropy but also a higher degree of information (Hidalgo 2015). That is, it says something about the energy and forces required to create and maintain it. Economic geography can then be understood as a social science aimed at describing, understanding and perhaps also predicting or preventing the heterogeneity and unevenness in the spatial distribution of social and economic activities.

Since economic geography is a social science, it requires some quite different approaches compared to the study of entropy of, for example, particles in a gas. To illustrate this, compare the example with the busy street in morning rush hour traffic from previous section with particles in a gas. The particles all obey the same laws of motion, acceleration and interactions – one particle is in theory interchangeable with any other of the same kind and with the same speed and direction. The people in the busy street also obey the laws of nature, how could they not, but they are not interchangeable. Apart from these common laws, they also follow rules of their own. This heterogeneity reflects not only variation in what principles govern each individual’s behavior but also differences in individual perceptions, i.e. bounded rationality (Simon 1997; Gigerenzer and Selten 2002). If one pedestrian is replaced by another, giving the replacement speed and direction will not be enough. This is because the street is a social system that self-organizes based on the preferences, plans and perceptions of each individual. Importantly, individuals differ both in terms of what they aim to achieve (getting to the office on time, grabbing a coffee or leaving the kids at daycare) and how they perceive the system they are part of (switching lanes to get there faster, noting the shorter line in another coffee shop or deciding on which is the faster way to get to daycare). This has important implications for how the aggregate system is conceptualized.

As a particle system grows in size, it quickly becomes impossible to track the position, direction and speed of every single particle. However, since they all obey the same set of rules, even if their individual interactions are messy, they can be studied on an aggregate scale. As the number of particles grow, the accuracy of statistical methods and distributions grows with it. This means that for large systems, the statistical distributions as well as mean-field approximations that simplify a many-body-problem to a one-body-problem give a good estimation of the system and its behavior. If there are only a few people there, it is possible to document their position, direction and velocity, and perhaps also to ask them about their objectives or preferences. As the number of people grows, this quickly becomes impossible just as for the particles. It is tempting to think that if the population of individuals becomes large enough, their differences will offset each other so that they can be approximated as a system of particles. This is both true and false. It is true if their individuality does not matter too much, for instance if we wish to model the congestion in the subway system. What matters then is the distributions of people at origins and destinations. If, however, we wish to model social interactions individuality will play a crucial role. While particles will bump randomly into each other subject to the same laws of particle motion, people will discriminate in their interactions based on for example relationships, preferences or mood, but also on their perception of the surrounding world. The resulting pattern of interactions is highly heterogeneous, but not random.

This nonrandom heterogeneity in interactions makes an important contribution to understanding urban life, but it is not unique to cities. It is part and parcel of general social network analysis, where the object of interest is often to map out relations between for instance individuals or firms to be able to learn more about their behavior. So far, cities are equivalent to online social networking platforms. What separates them, however, is that interactions within a city are anchored in space, or "situated" in the words of Holland (2014). All interactions are realized in some form of context, an interaction arena or structure that conditions the exchange. Just as internet acts as a medium to transcend physical space, the city provides a medium that utilizes physical space. This medium can be thought of in two ways: space, and place.

Space refers to the relation between interacting parts in terms of some distance metric. For instance, transport costs associated with meeting someone, including for instance time, energy and monetary expenses. Increasing geographical distance affects interactions negatively – as a rule of thumb interaction frequency can be estimated to decrease as one over the distance squared. This implies that geographical proximity increases the potential for interactions. It does not, however, mean that people interact with everyone they are near and no one far away. To make sense of this, consider social proximity as a complement to geographical proximity. Social proximity, or social distance, is a measure of the social connectivity between people (Borgatti et al 2013; Nooteboom 2000; Boschma 2005). In a random encounter, people are more likely to stay and talk with an old friend than a complete stranger. Conversely, social proximity can counteract geographical distance in the sense that people maintain relationships over long distances with people they share close relationships with.

With respect to space, the main feature of cities is that they concentrate a lot of people within short geographical distances, making it easier for people who wish to interact to do so.[5] Furthermore, there are empirical studies that suggest that geographical and social proximity tend to coincide, i.e. that people locate close to others they feel close to or identify with (Feldman and Tilly 1960; Hipp and Perrin 2009). In addition, through geographical proximity people are exposed to new potential interactions that promote social proximity among neighbors, co-workers or even people who frequent the same coffee shop. Density increases the chance for meeting new people, especially if you want to do so. This leads to the role of places.

While distance can roughly be treated as a measure of pairwise isolated interactions, places provide a context that sets different interactions, as well as new potential interactions in relation to each other. Batty (2013) conceptualizes location as a synthesis of overlapping subsystems of interactions. Consider the example of advertising firms on Madison Avenue from previous sections. It is a place that exhibits empirically observable but also highly localized productivity benefits for advertising firms situated there (Arzaghi and Henderson 2008). It is also a place that attracts a wider selection of people interested in advertising, and it is widely known as a hotspot for advertising to people who have never even been in the U.S through popular culture references such as the TV-series "Mad Men". In this sense, the place Madison Avenue acts as a coordination mechanism for interactions related in some

[5] There are still issues of congestion, differences in accessibility and time distances within cities, and these problems are likely to grow with the size of the population, but overall cities increase the number of potential interactions.

way to advertising. What makes this especially interesting is that as a place becomes known for a certain type of activities, the interactions going on there as well as there potential spillovers are made available to new individuals without previous social proximity to these activities. Along this vein, Rose (2016, p. 6) uses the concept of ecological niches as “a useful way to think about neighborhoods as nested in the systems of the city”. This geographic scope captures both the localized agglomeration externalities and the potential of positive reinforcement, self-organization and emergence associated with complex adaptive systems. Conversely, from an individual point of view Hägerstrand (1970) describes how people are limited in connections and capacities related to time, space and coordination with others. Put differently, people never geographically and socially access the whole city simultaneously but are naturally anchored to a series of places going for instance from their homes to their workplace.

As with all models and modelling frameworks, it lies beyond this thesis to capture the full variation of geographical relations associated to distance and places. For that reason, the papers and the overarching framework presented here are focused primarily on places and their role as local interaction structures within the city. Localized agglomeration externalities that are assumed to generate productivity benefits can be expected to concentrate on average around workplaces. Therefore, they be approximated with a combination of overall employment density and the concentration of different individual-level characteristics such as education or sector of employment. That is, a place is treated as the combination of density measures consisting of the presence of individuals and firms with certain characteristics and the activities they engage in there. These places can be thought of as a local compartmentalized approximation of the overlapping subsystems of interactions and networks proposed by Batty (2013). The resulting approximation provides a measure of heterogeneity, or unevenness within the city which can be studied through the lens of complex adaptive systems to uncover patterns and principles of urban life.

There are two immediate caveats to this approach. First, it misses the explicit network links between people that are the main concern of social network analysis. While this is true, studying the local environment, for instance around workplaces, provides an important proxy of where work-related non-market interactions that generate some type of informational or knowledge spillover may occur. That is, complex adaptive systems are assumed to rely on networks of interactions, but explicit links or interactions may not be described or predicted in detail. West (2017, p. 27) states that these systems rely on their networks to sustain their properties:

> *"Highly complex, self-sustaining structures, whether cells, organisms, ecosystems, cities or corporations, require the close integration of enormous numbers of their constituent units that need efficient servicing at all scales. This has been accomplished in living systems by evolving fractal-like, hierarchical branching network systems presumed optimized by the continuous 'competitive' feedback mechanisms implicit in natural selection. It is the generic physical, geometric, and mathematical properties of these network systems that underlie the origin of [...] scaling laws"*

While the individual links remain implicit in this approach, the effect of the local interaction structure is highlighted. In the mapping of individual links, the opposite is true. A certain phenomena is projected onto the observed network, but tends to disregard the local context as well as the links that did not make the cut in the mapping. For example, a co-worker network may miss out on a interaction between two old friends working in the same neighborhood and exchanging knowledge that leads to a new innovation. There is no absolute right or wrong answer to whether it is better to study neighborhoods or networks. Instead, it depends on what question the analysis addresses. Since the focus here is on within-city variation in agglomeration externalities and informational spillovers, places allows for a greater focus on the city as unit of analysis, rather than individuals or individual links. The second caveat is related to the relation between places. A typical example of such relations is the individual links between home and workplace that give an indication of how certain parts of the city are related to each other. Looking exclusively at local places omits connections between them, but also individual links between different types of local interaction structures. This line of inquiry is a promising venue of future research and a natural continuation of the framework presented in this thesis.

Against this background, it should also be noted that the role of interdependent interactions is not new to economic geography. Within the relation and reflexive strain of economic geography, Storper (1997) underlines the role of *reflexivity*, which implies the system's or a collective's ability to "reflect about the functioning of their environment in a way that is not limited by existing parameters" (ibid, p. 29), and *untraded interdependencies*, which includes localized "conventions, informal rules, and habits that coordinate economic actors under conditions of uncertainty" (ibid, p. 5). Both of these concepts are echoed to some degree in the view on complex adaptive systems advanced here. Reflexivity can be crudely described as a form of adaptation that is not not simply a knee jerk reaction to the system's external environment, but may be derived from aggregated expectations. Untraded interdependencies could be said to describe emergent phenomena, i.e.

macro-level system properties that derive from individual behavior, interactions and coordination over time and give a place its unique locality.

An even closer relation to interdependent interactions is found in the strain of research dedicated to evolutionary economic geography, which combines path dependency theory, general Darwinism and complexity theory (Boschma and Martin 2010). Apart form directly relating to complexity theory, both path dependency theory and general Darwinism rely on the interdependency of interactions to describe one the one hand irreversible historical trajectories or "paths" as well as the selection related to evolutionary development. In both cases, the outcome of a single actor's behavior depends heavily on which other actors are present and what they are doing. The addition of complexity theory to the evolutionary economic geography framework is, however, less pronounced than that of path dependency theory and general Darwinism (Boschma and Martin 2010; Martin and Sunley 2007).

1.5 Aim, contribution and research question

Chapter one has introduced three fundamental modelling assumptions that conditions the scientific work in this thesis: (1) cities are systems of interdependent local social interactions that enable information flows and agglomeration externalities, (2) that these interactions constitute a complex adaptive system, and (3) that the complex adaptive system is anchored in places in the within-city geography. The chapters included in the thesis all address some aspect of these assumptions by consolidating them theoretically or empirically with current state of the art research. The kappa brings these different contributions together in order to formulate a wider theoretical framework to analyze the social and economic life of cities from a complexity point of view.

Every scientific endeavor requires a what, a why and a how. The *what* of this thesis, its aim, is to explore patterns of disaggregated within-city variations in agglomeration externalities, especially those associated to informational and knowledge spillovers, and leverage them to study the internal complexity of cities and local interactions as complex adaptive systems.

As for the *why*, the main contribution of the thesis is the development of a theoretical framework to explore the complexity of agglomeration and urban growth. It describes how interactions can generate self-organizing agglomeration externalities and productivity gains that scale with localized density measures within cities as well as with city size. This model is then tested against empirical regularities and the distribution of density-related externalities. This contribution is what Holland (2014) refers to as a "where to look" theory. The ambition is not to determine the origin of urban growth, but to suggest how productivity gains at different spatial scales may relate to each other through nonmarket interactions and what system properties they may adhere to on an aggregated scale. Zooming out, the main value of such a contribution is to provide the tools to formulate new questions about how the internal order and organization of cities may affect their aggregated behavior. This can help to relate the performance of growing as well as shrinking cities to their inner social and economic lives.

The *how* of a thesis is answered by formulating a research question and by putting the included papers in relation to that question. The overarching research question at the heart of the thesis is whether local social interaction systems really form complex adaptive systems or not, but in order to make the issue more approachable it is divided into two more tangible sub questions:

- *Do local social interactions within cities form complex adaptive systems that affect agglomeration economies and by extension productivity and urban growth?*
    - *Is the distribution of localized agglomeration externalities within cities, especially those associated with informational spillovers, consistent with self-organization and complex adaptive system properties?*
    - *How can within-city agglomeration externalities and city-wide productivity gains related to city size be described and explained in terms of complex adaptive systems?*

The thesis includes four papers that address these questions in different ways. Papers 1 and 2 relate directly to complexity and a complex adaptive system framework. Paper 1 introduces a theoretical conceptual model of nonmarket interactions as a form of collective information processing or collective learning. The model is consistent with empirical regularities for localized agglomeration externalities on a within-city spatial scale as well as empirical evidence of productivity gains scaling with city size. Paper 2 extends the framework from urban scaling analysis to empirically test for scaling based on employment density within cities. It employs a variety of regression tests that show evidence consistent with scaling between neighborhoods matching that between city sizes.

Papers 3 and 4 do not treat complexity or complex adaptive systems explicitly, but deal with the nature and structure of interactions and externalities. Paper 3 explores the competing views on industry specialization and diversity as a source of agglomeration externalities. The paper tests the hypothesis that both types of externalities may coexist but operate at different spatial scales. Specialized neighborhoods or districts can aggregate into a diversified urban economy. Results indicate that diversity externalities operate at both the neighborhood and the city wide level, while there are small indications of very localized externalities pertaining to specialization on the neighborhood level. These results contribute to the complexity framework by empirically exploring and testing a hierarchical or modular structure of interactions that is consistent with self-organization. Paper 4 explores the role of social capital in the economics of cities. More specifically, the paper presents a conceptual model that describes how interactions and the social capital they generate differ between rural and urban areas. The framework identifies different types of interactions, but specifically points out one type – infrequent and indirect interactions - that are unique to larger cities but may play an important role in transmitting behaviors, norms or attitudes. The conceptual model is matched with empirical evidence indicating that higher density of entrepreneurs in a neighborhood correlates with a higher degree of future entrepreneurship in that neighborhood. In a way, this paper is furthest away from the rest of the thesis, but the observations that cities not only consist of more of the same type of interactions found in a rural community, but also *different* types of interactions, is crucial to the framing of cities as systems of interdependent social interactions that are anchored in places.

Positioning this thesis is no easy task. Both complexity science and economic geography are strongly interdisciplinary fields of study, something that makes them ideal to combine but also makes the result hard to nail down to a single literature strand. Consequently, the thesis is not restricted to one specific literature, but rather to one specific type of problems: applying complexity and complex adaptive systems to agglomeration economies on a within-city scale. The result applies mainly to three strains of research, agglomeration economies, urban scaling analysis and evolutionary economic geography.

The combined theoretical and empirical results presented in the thesis contribute to the literature on agglomeration externalities by putting localized agglomeration externalities in relation to the city as a whole. If urban economies self-organize, then this conditions the existence of agglomeration hotspots in ways that have yet to be fully explored. To a lesser degree, the thesis also contributes to exploring the anchoring of interactions in locations and how this can create focal points for social and economic activities. The theoretical contributions resonate strongly with the evolutionary economic geography literature, but rather than to build on the complexity concept found in that framework (which is generally considered to be limited in scope) the thesis draws up the beginning of a somewhat different, alternative approach. With respect to the urban scaling literature, the thesis makes an important contribution by extending the scaling relationship between productivity gains and social interactions to a within-city spatial scale. First, this allows for some of the insights from urban scaling analysis to be transferred to a neighborhood level and explored in that context. Second, in a wider perspective it adds an alternative approach to discuss deviations in intercity scaling, i.e. to quantify local exceptionalism or failure with respect to scaling relations. This may in turn for instance enable scaling analysis to provide insights and recommendations to small or shrinking cities beyond that fact that they are small.

The strongest common denominators of the thesis is to highlight two aspects of the internal complexity of urban economies: First, that there are bottom-up organized patterns to cities' internal organization and that understanding these patterns adds a wider context to existing knowledge about cities and their future development. Urban interactions between individuals or firms give rise to emergent complex adaptive system properties that gives cities a "life of their own". Second, the complexity of the social and economic activities that make up urban economies mirror a growing complexity in society and the economy at large. More than a curiosity, complexity science provides a venue for questions related to both research and policy concerning how increasing interconnectedness and interdependence affects the world around us but also our ability to change it.

Chapter 2: Methodological approach

2.1 Finding complexity in theory and correlation

Complexity in and of itself is nothing new. Colaner and Kupers (2014, p. 47) observe that "scientists have always realized that interconnections matter, but because those interconnections were next to impossible to deal with, they quite understandably simplified". Following advances in computer technology and analytical tools, however, it is becoming feasible to approach these issues in new ways.

Complexity theory and complex adaptive systems as a scientific approach favors the macro-level aggregate system properties before the micro-level mechanisms that drive activities within the system. This limits what can be said about such mechanisms, and by extension also about causality. Miller and Page (2007, p. 20) argue identify a trade-off between the phenomena being studied and the the modelling approach taken in economics, but it applies equally to quantitative analysis in economic geography:

> *"In economics, formal modelling usually proceeds be developing mathematical models derived from first principles. This approach, when well practiced results in very clean and stark models that yield key insights. Unfortunately, while such a framework imposes useful discipline on the modeling, it can also be quite limiting. The formal mathematical approach works best for static, homogeneous, equilibrating worlds. [...] Thus, if we want to investigate richer, more dynamic worlds, we need to pursue other modeling approaches. The trade-off, of course, is that we must weigh the potential to generate new insights against the cost of having less exacting analytics."*

Complex systems are said to be "larger than the sum of their parts" – an argument used to oppose the reducibility that is implicit in many other scientific lines of inquiry. This is both true and not. If complexity is a system property, then by definition a complex system cannot be fully described by the sum of its parts. This does not entail that new insights cannot be gained by disaggregating a complex system (which I do in paper 2). In fact, the notion of self-similarity or fractality in complex systems suggest that some structure of the system is maintained and repeated across spatial scales. A more apt description might be that the system scales nonlinearly with size – instead of aggregating to the linear sum of its parts it adds up to something more, or different. What this implies for a scientific analysis is that the conclusions that can be drawn from such exercises are constrained by the fact that they omit features that emerge only at the level of the whole system. This mirrors the issue of Marshallian equivalence found in studies on agglomeration economies. Marshallian equivalence means that several different configurations of micro-level settings can result in the same macro-level outcome.

If the objective of the scientific inquiry is to isolate and explain micro-level actions or mechanisms, this is indeed a problem. If, on the other hand, the aim of the analysis is to describe macro-level system properties, then it is not a problem. Similarly, complex adaptive system models may lack in the ability to predict individual behavior within the system, but they are all the more geared towards predicting system-wide properties and behavior, like for instance how the growth or crime of cities change with their scale in urban scaling analysis (West 2017).

The criteria for investigating micro-level mechanisms and aggregated system properties must be differentiated from each other. Because system properties, in accordance with Marshallian equivalence, can result from several different compositions of micro-behavior, the use of the concept of causality becomes much more constrained. Returning to the example of urban scaling analysis, when "scaling laws" are predicted, the city is effectively treated as a black box and the only measures used is the aggregate socioeconomic output in relation to population size. This approach cannot readily explain difference between two cities of equal population size or why a city differs from the predicted outcome in relation to its size.

Applying complex system analysis on a within-city scale makes this friction between reducible and irreducible lines of inquiry even starker. While the econometric analysis normally applied to studies of agglomeration economies strive to isolate a driving factor, a complexity-based approach is concerned with how the interactions between people or between parts of the city form patterns or generates emergent phenomena. In other words, the former aims to predict the influence of one factor on one outcome, while the latter aims to predict system patterns and properties without distinguishing between the different micro-level activities that may generate them.

Approaching the golden standard of causality comes at the cost of removing information that goes into the model. By definition, what a good test of causality does is to strip the empirical context of all its traits until ideally only the independent and the dependent variable remain, to produce more detailed outgoing information about their relationship. In contrast, a correlation model provides a richer set of information with the obvious caveat that it contains the overlap in influence between factors and noise generated for instance by the locality of the empirical observation. Holland (2014, p. 45) argues that the urge to include and distinguish between more details in a model "stems from an instinct for 'realism', which leads to requests for more and more 'verifying' details" but that this should be resisted because "a model's clarity and generality depend directly on how much detail has been set aside". There is a trade-off between setting details aside or including them that comes down to what type of question you want to answer. Correlation is a workhorse of pattern recognition at an aggregated level. Put differently, correlation captures the "whole" that contains system properties associated to complex adaptive systems.

In a similar manner, Miller (2015) describes the complex system approach as a search for *true places* – that which cannot be captured by a map however detailed it may be precisely because it is messy and noisy. He argues that:

> *"Reductionism fails because even if you know everything possible about the individual pieces that compose a system, you know very little about how these pieces interact with one another when they form the system as a whole."*

In principle, this is true since the original motivation of the reductionist approach is that *everything* can be explained by picking it apart like a complicated (but not complex) clockwork. However, in practice it is only partly true since studying the whole alone would provide an equally partial image for someone interested in understanding what the system consists of. Returning to the map analogy, Miller and Page (2007, p. 37) notes that "[g]ood maps not only allow us to predict key features of the world, but they also enable us to discover new phenomena". Applying complexity science to economic geography has the potential to do just that.

Putting correlation against causality, or for that matter complex models against more traditional economic models, ultimately proves to be a false dichotomy. Page (2016) makes the case that complex models and traditional equilibrium models should be treated as complements rather than substitutes:

> *"First, the standard model [in economics] and the complexity model differ substantially. The value of a pair of models depends on how much they differ. It is far better to have two dissimilar models than two nearly identical models. Second, the complexity-based model need not be better than than the equilibrium model to be of use. It need only be not substantially worse."*

Page goes so far as to ascertain that unless the complexity model produces an error that is twice that of the traditional model, it will contribute significantly to the accuracy in explaining phenomena simply because it provides the other half of the picture. This thought experiment is an important one, for advocates of complexity should not make the mistake of thinking that their approach should replace reductionism in an attempt to explain everything.

There is a relation between theory and model. Working with complex systems and correlation puts a different emphasis on theory and theoretical frameworks.[6] A study on the causality between drinking alcohol and becoming intoxicated can to some degree substitute theoretical argument (about how alcohol affects the body biologically) with control variables or instrumentation and still make its point fairly well (drinking gets you drunk). In contrast, a study on the power law distribution between employment density and wages must rely on a more thorough theoretical framework to allow deductive conclusions based on the result.

Holland (2014) differentiates between three model tactics: Data-driven (parametric) models, existence-proof models, and exploratory models. Data-driven models are well apt for making identifying mechanisms and making predictions based on large sets of data, typically associated with traditional econometric models. Existence-proof models are aimed at showing that something is *possible*, but does not evaluate the underlying mechanisms. Exploratory models are used to evaluate if a given set of mechanisms can generate a specific type of empirical observations, i.e. what happens when these mechanisms interact with each other. This does not prove that the specified mechanisms are present in the observed system, but aims at providing

[6] Note that all empirical investigations must be preceded by theory, or it would not be possible to formulate questions and hypotheses. Despite this, theory is sometimes downplayed in favor of empirical work.

a result that is consist with the idea that they could have been. The latter two require amore rigorous theoretical framework, to avoid a too wide range of interpretation of results and their consequences. This however, does not mean that theory needs to be more detailed, i.e. cover more details or parameters, in order to be rigorous. In describing the framing of urban scaling analysis, West (2017) calls for the need of *coarse-grained* descriptions and theories that address what he refers to as the average salient features of the system under study. This thesis relies predominantly on exploratory and existence proof model tactics to identify complex adaptive system properties and to formulate coarse-grained descriptions and theories to link them to agglomeration externalities and to local social interactions.

Speaking to the broader advantages of theoretical or theory-heavy work in economic geography, it travels lighter across geographical distance, contexts and national borders. Theoretical work produced by someone in Stockholm, can be read, critiqued and elaborated by someone in Tokyo. Similarly, correlation studies present more general, i.e. less stripped-down and specified, features that can on average be more readily expanded to new geographies. Put differently, increasing detail in studies of causality correlates within rising friction in transferring or translating the results to new geographical, cultural or social contexts.

The approach I take in this thesis is based on the assumption that complexity and complex adaptive systems complement the traditional scientific analysis of cities, but does not replace it. I develop a theoretical framework that relies on both theory and empirical findings in both complexity science and economic geography as well as related fields of study. This transdisciplinary link is, I believe, fertile soil for real scientific progress on cities.

2.2 Empirical considerations

The empirical investigations carried out in the papers included in this thesis rely exclusively on highly disaggregated and geo-coded data from Statistics Sweden. Firm- and individual-level data is associated to a square grid of 250 by 250 meter cells (which are also aggregated together into 1 by 1 km cells to provide a larger "neighborhood" unit. The grid is exogenously defined, without any consideration to how the lines cut space. This means that each observation is spatial "boxing" of data to be compared or correlated within and between boxes. The upper limit of demarcation for the city is set as the local labor market region, providing a functional unit of analysis rather than an administrative border.

One drawback is of course that the cells do not reflect functional neighborhoods or neighborhood identifies as perceived by people living there. Strictly speaking, what is being studied is highly localized co-occurrence between for instance density and wages. An intuitive objection is that firm- or individual-level data associated to firms or individuals at the edge of one cell may be affected more by the neighboring cell. This is addressed either by controlling for the influence of first order neighbors (in Paper 3) or by including several cell sizes to test for robustness across spatial scales.

Because complex adaptive systems consist of many interdependent interactions that make up networks, it may not be evident that the unit of observation should be neighborhoods rather than networks. This point has been raised briefly before, but deserves some elaboration. The type of interactions mainly considered here are local social interactions, i.e. interactions that are situated in space which is often the case for complex adaptive systems whether it is physical space or some other form of interaction structure (Holland 2014). Local interactions do not imply that any two people close enough will interact, but that geographical proximity raises the potential for interacting and influencing each other direct and indirectly. Commenting on the related field of neighborhood effects in economics, Durlauf (2004) argues that "one can think about a neighborhood as a set of agents who are all capable of mutual communication via the network", i.e. who are linked to each other in a social network. On a similar note, Glaeser (2000, p. 103) emphasizes the spatial dimension of non-market interactions:

> *"Spatial proximity (and hence urban density) facilitates the first kind of non market interaction [direct], as proximity makes reciprocal relationships easier to start and maintain. The second kind of interaction [indirect] even more strongly depends on spatial proximity. In many cases, these effortless transmissions of ideas and values depend on sight or hearing. Even if the affected person has not seen or heard the influential person himself, it is often true that he knows someone who has had this personal contact. Obviously, the ability to see or hear depreciates sharply with space"*

Furthermore, the technical and mathematical toolboxes are similar for network analysis and neighborhood effects, although the conceptual motivation differs. Social network models can use geographical distances and adjacency or co-location as aspatial links, just as several spatial models can also be applied to non-physical networks (Gibbons et al 2014).

A downside of studying places instead of networks is that it is hard if not impossible to determine explicit causal relationships between individuals. Manski (1993; 2000) investigates models of social interactions and distinguishes between endogenous social effects (influence from the *decisions* of the other members in the neighborhood) and exogenous social effects (influence from *characteristics* of the groups that the individual belongs to, including the neighborhood) and argues that these two types of effects are extremely hard to separate (the so called *reflection problem")*. This is, however, not that much of a limitation in the study of complexity and complex systems since the scope of pinning down causality and making predictions is already limited.

Chapter 3: Theoretical framework and literature review

3.1 the city is not the atom

"Physics makes much use of the concept of "elementary particle" although particles have a disconcerting tendency not to remain elementary very long. Only a couple of generations ago, the atoms themselves were elementary particles; today, to the nuclear physicist they are complex systems."

- Herbert Simon

What is a city? Cities have had a variety of different functions historically, from sanctuary beyond city walls and local market place to manufacturing hub during the industrial revolution and hotspots for innovation in an increasingly knowledge-intensive economy. One thing that has remained the same through all these roles is that cities concentrate people and their interactions with one another in space. In other words, the constant of cities is that they are systems of social interactions.

The city is often made out to be an indivisible unit of analysis. Cities are said to be successful, vibrant, failing, attractive, growing, or shrinking. A wide variety of societal characteristics including economic growth, productivity, innovation, crime and congestion are assumed to be the outcome of the city as a whole. Yet beyond size and behind the bricks and mortar, cities consist of complex and adaptive patterns of interactions between individuals distributed across and anchored in locations. The city is not the atom of the analysis but a complex molecule and, just as in chemistry, comparing molecules to each other without regard to their internal composition and configuration will leave out important information.

In this part of the thesis, I review research literature on a series of subjects that logically and empirically connect social interactions with localized agglomeration externalities and productivity gains, information flows and complex adaptive systems. This chapter consists of five parts that all bring in partly different but overlapping literatures: Density and agglomeration economies, internal order, information and interactions, evolution and complex adaptive systems. Each part is presented in a way that is largely self-consistent, but connections are made between parts. In particular, connections are made to complexity and complex adaptive systems throughout the chapter. Following 3.2-3.6, 3.7 summarizes the papers included in the thesis, and finally 3.8 addresses the research questions

3.2 Density and agglomeration economies

The existence and formation of cities has historically been described not so much in terms of proximity as in distance or the lack thereof. In fact, many of the foundational models of cities and the spatial organization of economies focus on the transport costs associated with moving goods and people across space within or between cities (von Thünen 1826, Christaller 1933, Lösch 1954, Alonso 1960, Krugman 1991, Fujita et al 1999). Von Thünen formulated a model of bid-rent curves to describe the allocation of farm land around a city center as the outcome of competition between different types of products. The outcome in equilibrium is a set of concentric circles around the city center that result from a trade-off between the yield of the land-use and the cost of transporting the products to the city center to sell them. This outcome is associated with a nonlinear rent gradient falling from the city center to the outmost land patches.[7] Although the models have changed since von Thünen's time, the rent curves remain a strong characteristic of land-use in cities.

In central place theory, as formulated by Christaller and later developed by Lösch, the allocation of people and economic activities across settlements is explained in terms of a balance between demand and land use. Frequently demanded goods and services are supplied locally in *low order settlements*, while those that are less frequently demanded are supplied in *high order settlements*. In Lösch's development of the theory, local low order settlements form smaller hexagons that collectively form a larger hexagonal around high order settlements. The logic behind central place theory also resonates in the planning of satellite towns in the British *New Town* movement or the Swedish *ABC-areas*.

[7] Fujita and Thisse (2013, p 16-17) underline a strong link between the arguments made by von Thünen concerning industrial agglomerations and the model proposed by Krugman (1991) in what has become known as New Economic Geography.

What happens when the conditions for transports change? Glaeser and Kohlhase (2004) find that the cost of transporting goods in the U.S. have declined by over 90 percent during the 20th century, while technological progress has made transports more independent of fixed transport routes. On the other hand, while it is cheap to transport goods it is expensive to move people. Glaeser and Kohlhase make two interesting observations about the mobility of people. First, the conditions for moving within the city has changed tremendously with the introduction of the car. Instead of accessing the city by foot from central nodes in public transportation, people can drive or take a cab to a specific district and then walk around. This enhances the individual's access to the city. On the other hand, growing cities face the challenge of growing car fleets, congestion and pollution. This amounts to increased transportation costs for people to and within cities. They conclude that "Cities are best regarded as the absence of physical space between people and firms" and that there is a need for updated models that capture agglomeration and the gains from interaction and face-to-face contact. In other words, a slight but significant move of focus away from distance towards proximity (Glaeser 2011, p. 6).

With the rise of globalization and the development in communication technologies at the end of the 20th century, there was a growing belief that this would be the "death of distance".[8] By extension, this would also mean the end of cities. Existing peaks in the economic geography would flatten out (Fujita and Thisse 2013, p. 1). Why would anyone pay high rents and endure congestion if the economic playing field was being levelled globally while all communications and information was just a click away? This did, however, not turn out to be the case. Instead, the world is becoming more urbanized and the economic geography more uneven in space. Urbanization and digitization appear to be complements rather than substitutes (Wernberg and Andersson 2016). They both contribute to making it easier for people to interact with each other. Cities bring people together locally, but also gather the necessary demand for international travel to make cities hubs in a global travel network of places. Digital technologies makes it easier for people to find each other and to stay in touch, both near and afar.

Proximity is a necessary, but insufficient condition to make a city on its own. In other words, people do not live in cities to be near other people, but for what that proximity makes possible. Going back to the late 1990's, Glaeser (1998, p. 141) responded to the speculations about the coming death of the city and concluded that the issue is whether or not the advantages of proximity outweigh the disadvantages:

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[8] This was the title of a article in the Economist (September 30th, 1995) and later also of a book, both by Frances Cairncross.

"The ultimate prognosis for cities depends on whether the changes in the benefits accruing to cities from informational spillovers and the division of labor will be greater than the changes to the congestion and the social costs of cities. I believe that the death of the city is far from imminent."

The informational spillovers that Glaeser refers to are generally described as agglomeration economies, or external economies of scale. The spatial configuration of economic activities in a city is the outcome of a complicated balance between centrifugal forces pushing towards dispersion and centripetal forces pulling towards agglomeration (Fujita and Thisse 2013, p. 9). Agglomeration externalities are organizationally external to the firms located in a city, but geographically internal to the city.

The study of agglomeration externalities have led scholar to study what type of city and industrial composition provides the best conditions for local firms (Neffke 2009). A long-standing line of research is dedicated to whether industries in a city should be specialized or diverse in order to reap the benefits of agglomeration externalities (Glaeser et al. 1992, Audretsch and Feldman 1996). Put differently, the question is if externalities operate primarily within industries as spillovers of niche knowledge and know-how, or between industries as a means for generating new ideas and innovation.[9] Reviews of empirical studies show large ambiguities and suggests that additional conditions such as country, time period and differences between industries may matter for the outcome (De Groot et al 2008, Beaudry and Schiffauerova 2009). Roughly speaking, there are indications of agglomeration externalities, but there is no simple one-size-fits-all answer to the question of how to design a city to leverage them. This raises the question of what mechanisms generate agglomeration externalities in the first place.

Agglomeration externalities are theoretically motivated by different categories of micro-foundations, like sharing, matching and learning (Duranton and Puga 2004). Sharing refers broadly to the pooling of demand-side factors. For instance, a larger city can support a subway system even if the demand per capita is low because the aggregated demand meets the supply in a way that justifies the investment. In addition, as the city grows the infrastructure per capita decreases since the cost of making the subway system accessible to another person is low. Matching is perhaps

[9] Within-industry externalities are referred to as MAR externalities (Marshall-Arrow-Romer) while between-industry externalities are referred to as urbanization externalities or Jacobian externalities after Jane Jacobs.

best exemplified by the matching of supply and demand in the labor market. The number of matches but also the quality in matching improves with labor market (Ahlin et al 2014). Finally, learning externalities refer to knowledge spillovers and externalized flows of information and knowledge. In other words, learning externalities are exchanges of information between individuals that are external to firms but bound locally to the city. One way of thinking about it is that face-to-face interactions is still an unsurpassed medium for transmitting uncodifiable, tacit knowledge especially in local environments where information is changing rapidly (Storper and Venables 2004, Storper 2013).

The considerably different types of micro-foundations prompts the questions of how agglomeration externalities may very in spatial distribution and attenuation. For a long time, empirical research on agglomeration economies treated cities in many respect as club goods (Rosenthal and Strange 2004).[10] Emphasis has been on comparing cities to each other and it is implicitly assumed that even if cities are highly heterogeneous their agglomeration economies operate at a city-wide scale. Essentially, this means that the city as such has been treated as an aspatial unit of analysis. While such inter-city comparisons have yielded and continue to yield valuable insights about urban economies, they do not contribute more than indirectly to our understanding of what is going on within the city.

During the last decade, a growing number of studies have started employing new types of data to move beyond the whole of the city and study variations in agglomeration externalities. The findings reported from these studies provide good reasons to believe that the internal composition of the city may matter just as much as its aggregated size. This appears to be especially true for externalities related to learning and knowledge spillovers. Arzaghi and Henderson (2008) identify positive externalities among advertising firms on the renowned Madison Avenue in New York City, but also report that their findings dissipate within 750 meters. Rosenthal and Strange (2008) find that wages correlate positively with employment density within a radius of 8 km, that the effects are driven by the concentration of college-educated workers and that it attenuates sharply with distance. In a Swedish context, Andersson, Klaesson and Larsson (2014) report significant variations in employment density-wage correlations when comparing city-wide geographical scale to a disaggregated square grid of $1km^2$ neighborhood cells. They furthermore find that the effects are larger and attenuate more sharply for college-educated workers. These evidence are consistent with the notion that learning externalities

[10] This is largely a data-related issue, because disaggregated and detailed data are hard to come by. Nonetheless, it has important implications for the knowledge produced about cities and urban economies.

and knowledge spillovers related to knowledge-intensive industries or human capital-intensive workers are highly localized in nature and operate at scales much smaller than that of an entire city.

Paper 3 in this thesis leverages disaggregated data on a within-city spatial scale to put the long-standing issue of determining whether industrial specialization or diversity promotes agglomeration externalities in a new light. Instead of treating the relation between within-industry specialization or diversity in employment density as competing alternatives on a city-wide scale alone, we compare the effects on two spatial scales: neighborhood level (consisting of a grid of one square-kilometer cells), and city region corresponding to the local labor market region. The results show that diversity externalities operate both at the neighborhood and city-wide level, while there is a small effect of specialization externalities that are constrained to the neighborhood level. These findings are consistent with the idea that social interactions organize spatially within cities, and that a diverse urban economy can contain several highly specialized neighborhoods or clusters. This in turn beckons the question of what principles drive the internal order and organization of social interactions that can drive localized agglomeration externalities such as informational or knowledge spillovers.

Against this background, the city is far more than the reduction of transport costs or the increase in geographical proximity. Cities give rise to agglomeration externalities, some of which relate to learning and show signs of being highly localized in space and at least partly differentiating in which firms and individuals they include and affect. It is evident that there are significant differences not just between cities of different sizes, but also between different parts of a city. This calls attention not just to the size or density of cities, but to their internal order and organizational principles.

3.3 Internal order

Cities are inherently disordered according to Hall (1998, p. 611) who proposes two origins of this disorder: The city's size which requires more advanced technologies to provide basic resources like water, food or waste management and its diversity in people:

> *"Cities are quintessentially disordered places, infinitely harder to manage than small towns or villages. Bringing order to them – cleaning the streets, collecting the rubbish policing crime – consumes a large part of the energies of their citizens, a larger part than any one them would care to deploy. This chore is the price that these people pay for the advantages that come from living and working in cities: the negative externalities*
>
> *...*
>
> *It is not just that big cities have more people living in them; it is that they contain so many different kinds of people [...] living in almost infinitely complex social relationships. The traditional rural and small-town moral constraints, imposed through visibility and familiarity, and reinforced by customary social relations and by long-accepted religious inhibitions, here begin to break down."*[11]

The city is at once both the built environment, the location and distribution of its firms and residents and the social interactions they give rise to. The historian Leo Hollis (2013, p. 19) illustratively compares Marco Polo's account of Beijing to Jane Jacobs account of Hudson street in New York and concludes:

> *"These are two wholly different visions of what a city is. In Marco Polo's city, the space is described as grand streets and palaces; the city is its physical form. For Jane Jacobs, there is hardly a word spent on the fabric of the cityscape, which is solely the backdrop for the human drama of urban life. So where do we find the real city: in the fabric of the place or in the bustle of the people living there?"*

[11] Hall refers to this as the replacement of Gemeinschaft with Gesellschaft. This statement may be contrasted with Mumfords (1961, p. 19) argument that *"the embryonic sructure of the city already existed in the village"* which refers primarily to the social processes *"House, shrine, public way, agora – not yet specialized market – all first took form in the village"*.

The perhaps only possible answer is that the city is both, but that they must not be confused with each other. When Christaller (1933) formulated the foundation for what came to be central place theory, what he did was to seek an explanation in built environment and location choices for the economic activity he saw in the reality around him. Even if successful, this does not guarantee that the model can explain or predict how people would behave in another place or or context.[12] The author and science-writer Steven Johnson (2003) argues that the power of cities is that they are centralized in space but decentralized in function. It follows that even though cities are planned in form, they are unplanned in dynamics or, rather, that cities follow *one* centralized plan in form, but *many* decentralized plans in function.

In terms of change, cities move at several different speeds, all at once. The built environment and infrastructure is slow-moving and time resistant.[13] Where people and firms locate in the city is something that changes over time, much faster than the built environment itself. Still, location choices are associated with a degree of inertia and friction for at least two reasons. First, every move is associated with considerable work for the mover, regardless of whether they do it themselves or hire a moving company. Second, since space is a scarce resource in cities, every move needs to combine the availability of a desirable destination to move to with the resources to move from the current location. Characteristics, conditions and changes at this time scale lay the ground for the regularities of cities, their pulse, including home-work commuting.[14] However, the everyday life of the city is found on a much faster time-scale. Most of what makes a city vibrant is what happens when people interact with each other and meet face to face. This is what gives a city its nightlife, its cultural district, and its startup coffee shops but also its crime, congestion and the rapid spread of the influenza.

Considering the internal order of a city, these different time-scales need not be be ordered in the same way. The order that describes the built environment is related to, but far from the same as the order applied to location choices or social interactions (Batty 2013, p. 28). The order that describes location choices may be more closely related to that of social interactions than of built environment, but they are still not the same. One way of understanding them is to consider how they relate to each other bottom up, from the fastest to the slowest.

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[12] Having said that, central place successfully describes the fractal nature of the distribution of city sizes, but it has its lower boundaries when people start interacting between these places.
[13] This could also be said of the formal institutions that govern the city.
[14] See for instance John Reads visualization of commuting patterns in London from 2012: https://vimeo.com/41760845

Social interactions can adapt instantly to location choices and built environment since both move considerably slower. For instance, if a popular restaurant closes, people will not simply substitute it for the closest other restaurant. Location choices can adapt rapidly to built environment, but adapt slowly to social interactions. That is, a firm can choose to locate close to the subway but can only hope to locate in a popular area with a lot of social life, since this is something that can change quickly. Built environment in turn may hope to cater to both location choices and social interactions, but can take none of them for granted. For instance, a residential neighborhood with mostly old residents can shift to a majority of families with small children.

Weaver (1948) introduced a distinction between problems of *simplicity*, *disorganized complexity* and *organized complexity*. Simple problems are well-defined problems of linear dependence that are fairly straight-forward to solve, like predicting the trajectory of a ball on a empty pool table. Problems in disorganized complexity depend on very large numbers of variables. This calls for solutions that rely on statistical distributions, e.g. tools from statistical mechanics, and shifts focus form the particulars of the micro-level behavior to the more accurate prediction of the macro-level properties of the system (Wilson 2011, p. 2). Finally, Weaver describes problems in organized complexity as poised in between the extremes of simple and disorganized complex problems. They may contain large numbers of variables, but more importantly they exhibit some degree of order (Weaver 1948, p. 5):

> *"Is a virus a living organism? What is a gene, and how does the original genetic constitution of a living organism express itself in the developed characteristics of the adult? Do complex protein molecules "know how" to reduplicate their pattern, and is this an essential clue to the problem of reproduction of living creatures? All these are certainly complex problems, but they are not problems of disorganized complexity, to which statistical methods hold the key. They are all problems which involve dealing simultaneously with a sizable number of factors which are interrelated into an organic whole. They are all, in the language here proposed, problems of organized complexity."*

Jacobs (1961) is considered one of the first to connect the concept of complexity with cities and urban planning. In doing so, she countered urban renewal and the *functional city* planning ideal pioneered by Le Corbusier and the Congress of

Modern Architecture.[15] What she describes as problems in organized complexity is on the one hand the social dynamics of the city, and on the other hand the interaction between the physical environment and the social dynamics. Along the same vein, Webber and Rittel (1973) put forward the argument that there is a distinct difference between the type of problems that natural scientists and engineers deal with, *tame problems*, and urban planning, which has inherently *wicked problems* that are ill-defined, interrelated and lack a definitive solution to end them.[16] Batty (2013, p. 15) similarly warns that planning should not focus on manipulating patterns of locations, but on why people come together in the first place.

Even when attempting to distinguish the social dynamics of the city from its physical form, the city appears to be a complex interplay between the two. One way of conceptualizing not only this interplay but also its different types of order involved is to employ Hayek's (2012, p. 34-52) differentiation between made order (*taxis*) and grown order (*kosmos*). Taxis refers to order that is simple, concrete and serves a purpose - organizations. Kosmos is a spontaneous form of order with a degree of complexity that is not limited to what human minds can master, abstract insofar that it is not necessarily manifested to our senses, and cannot be said to have a particular purpose. In other words, spontaneous order or kosmos can be described as the aggregate outcome of many individual but interdependent decisions. Hayek (2012, p. 45) states that:

> *"What in fact we find in all free societies is that, although groups of men will join organizations for the achievement of some particular ends, the co-ordination of the activities of all these separate organizations, as well as of the separate individuals, is brought about by the forces making for a spontaneous order. The family, the farm, the plant, the firm, the corporation and the various associations, and all the public institutions including government, are organizations which in turn are integrated into a more comprehensive spontaneous order."*

Combining the difference between taxis and kosmos with the separation of the city's physical form and built environment on one hand and its social and economic dynamics on the other, it is possible to sketch a map of the internal order(s) of cities (Figure 3).

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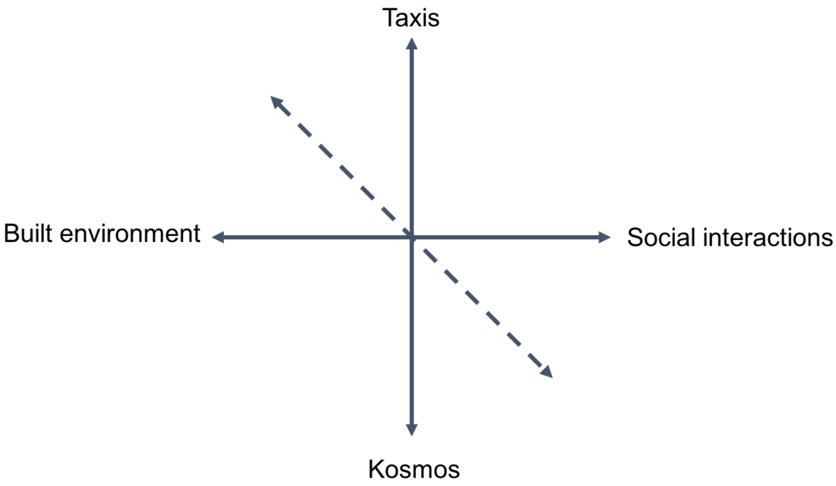
[15] According to Rose (2016, p. 3), Le Corbusier was inspired by Pythagoras's golden ratio and believed it to be ideal to determine the distance between building and their height-width ratios.

[16] Jacobs (1961, p. 433) similarly states that *"[Cities] do not exhibit one problem in organized complexity, which if understood explains all. They can be analyzed into many such problems or segments which [...] are also related with one another."*

Figure 3: Layers of internal order and adaptability



Comment: Combining the distinction between top-down made order (taxis) and bottom-up grown order (kosmos) with the difference in change and adaptability ranging from the physical form of the city to its social and economic life provides a conceptual map of different layers of the city's internal order. In the upper left corner, built environment is associated with more taxis and slower change or adaptability, while in the bottom right corner social interactions are more strongly associated with kosmos and quicker change and adaptability. On the diagonal line between these two extremes are for instance formal and informal institutions, firms' location decisions and the housing market.

The difference between Weaver's problems in disorganized and organized complexity is what Hayek calls spontaneous order. It describes why the social and economic life of cities is neither ordered along a centralized plan nor randomized. Rather, urban life is self-organized from the bottom up, something that is characteristic of complex adaptive systems (Batty 2013).

Self-organization offers some partial explanation to the persistence of cities and their characteristics over time. West (2017, p. 33) compares cities to companies with respect to the diversity and specialization of their economic activities and finds that while companies, typically organized predominantly top-down, tend to narrow their product space cities, which have a stronger presence of self-organization, tend to become more diverse with size:

> *"As they grow, companies tend to become more and more unidimensional, driven partially by market forces but also by the inevitable ossification of the top-down administrative and bureaucratic needs perceived as necessary for operating a traditional company in the modern era. [...]*
> *Cities, on the other hand, become increasingly multidimensional as they grow in size. Indeed, in stark contrast to almost all companies, the diversity of cities, as measured by the number of different kinds of jobs and businesses that comprise their economic landscape, continually and systematically increase in a predictable way with increasing city size"*

West also observes that while most companies tend to die within a human lifespan, there are few examples of cities dying. Cities persist under the dynamics associated with both in- and outward migration as well as the shift of generations, the rise and fall of companies and shifts in the economy. Colander and Kupers (2014, p. 49) observe that "[w]hat might appear to be a stable macro equilibrium is actually the outcome of an underlying micro disequilibrium of constant change". As a side note, it is intriguing to think about how much effort a company can put into establishing and maintaining a company culture, compared to how persistent the stereotypical mentality of people in New York City, Stockholm or Paris appears to be.

The distinction between made order and grown order also underlines how regulation and self-organization can coincide in cities. The different time scales described above act as different layers of an adaptive or evolutionary process in the sense that it is shaped by interdependent interactions at each level and between levels. The slower time scale associated with built environment is also more strongly related to regulation, while at the other end social interactions are realized on a faster time scale and are less constrained by regulation.

The distinction between the physical and the social city should not be thought of as a mutually exclusive distinction. A city's physical form and functions are governed by a number of institutions and formal rules including urban planning, a made order in Hayek's words. Even so, the different speeds of the city can be used to describe how physical places and urban social life interact with each other. Consider a simplified example: If enough people start frequenting a new club in an otherwise anonymous neighborhood, they bring attention to that place among a wider nightlife crowd and can set off a spiral of positive reinforcement that bring increasingly more visitors to the club. In return, other entrepreneurs may want to set up shop in that neighborhood, again adding to the positive reinforcement. Conversely, a neighborhood can also loose its luster if people go elsewhere. These effects on economic and social life can in turn affect urban planning strategies for the more slow-moving built environment. In a more generalized form, this argument can be applied to issues of gentrification, segregation, or diversity but it also stresses that these issues are not purely physical or social – they are an interaction between the two.[17]

Zooming out, the internal order of cities can be described in terms of *entropy*. According to the second law of thermodynamics, the internal entropy of an isolated system of gas particles, and by extension all physical systems, will increase over time. What this means is that the order of the particles will tend towards randomness because organizing particles from each other or in space requires more energy than to spread everything out evenly. What it also implies is that order requires energy to be maintained and that increased entropy correlates with decreased order, or increased disorder. Remember Hall's (1998, p. 611) description of cities as "quintessentially disordered" and constantly requiring work to remain ordered both physically and socially. Wiener (1954, p 28-31) in his ground-breaking formulation of the subject of *cybernetics*, makes the following argument to bring entropy into the social and societal context:

> *"As we have said, nature´s statistical tendency to disorder, the tendency for entropy to increase in isolated systems is expressed by the second law of thermodynamics. We as human beings, are not isolated systems. We take in food, which generates energy, from the outside, and are, as a result, part of that larger world which contains those sources of our vitality. But even more important is the fact that we take in information through our sense organs, and we act on information received.*
>
> *...*
>
> *Therefore, in the world with which we are immediately concerned there are stages which, though they occupy an insignificant fraction of eternity, are of great importance for our purposes, for in them entropy does not increase and organization and its correlative, information, are being built up."*

Cities form a pinnacle of such stages of reduced entropy which are temporary with respect to the evolution of the physical universe but long-standing and resilient with respect to human life-cycles. This would in turn imply at least three principle conclusions. First, cities are open rather than closed systems. This means that they depend on resources from the outside to maintain their internal order and workings. In other words, no city is an island. Second, since cities are open systems, they are

[17] Batty (2013, p. 20) refers to the focus on the physical side of the city as "physicalism".

subject to feedback from the outside and cannot be expected to remain in constant equilibrium. They may exhibit equilibrium temporarily, but they are by definition non-equilibrium systems (Batty 2017).

Third, cities can be defined bottom-up as local pockets of declining entropy and increasing order and information, fueled by the human beings that inhabit them. It follows that the dynamics and orders at slower time-scales are footprints of the social and economic activities that contribute to reducing entropy and increasing order and information. This approach resonates strongly with Batty's (2013) description of cities as interactions, networks and flows and locations as "the synthesis of interactions". Interestingly, this also echoes Mumford's (1961, p. 9) descriptions of the first cities:

> *"[Even] before the city is a place of fixed residence, it begins as a meeting place to which people periodically return: the magnet comes before the container"*

3.4 Information and interactions

> *"Now when we speak of an information-rich world, we may expect [...] that the wealth of information means the death of something else – a scarcity of whatever information consumes. What information consumes is rather obvious: it consumes the attention of its recipients. Hence a wealth of information creates a poverty of attention"*
>
> \- Herbert Simon

Cities not only concentrate interactions between people and firms in space and time, they also accumulate *information*. Communication technologies like writing and accounting were invented in cities (Hollis 2013, p. 12), most of the records and archives that make up our collective memory come from cities and even ancient cities themselves have imprinted in the earth *"layers of human occupation"* that make them a crucial information bank and a link to humanity's past (Parack 2012). It is in the combination between information and local interactions that cities attain the knowledge spillovers and external flows of knowledge and ideas that give cities their "genius" (Duranton and Puga 2004, Storper 2013, p. 156-167). This prompts the question of how information is related to the internal order of urban life.

There are many different definitions of what information is, but for the purpose of this analysis it is defined broadly as the opposite of entropy. Declining entropy expresses some degree of increasing order which corresponds to growing information (Wiener 1954, Hidalgo 2015).[18] Information is not, however, the same as meaning (Shannon and Weaver 1963). Hidalgo (2015), drawing on Schrödinger (1992), argues that information *is* physical order because solids are essential to maintaining reduced entropy in the world.[19] I propose that physical order is essential to maintaining reduced entropy in the physical world, just as knowledge and know-how are essential to maintaining reduced entropy in our collective understanding of the physical world. This leaves an understanding of information as a blueprint for physical order in everything from smartphones to buildings and cities, as well as for knowledge and know-how.[20] This echoes Hayek's (1945) description of the price mechanism as transmitting information about supply and demand in a market characterized by spontaneous order.

Endogenous growth theory plays a crucial role in connecting information to economic growth based on the assumption that ideas are non-rivalrous and enable scale economies (Glaeser 1994).[21] While Romer (1986) introduced the accumulation of knowledge as a source of externalities and growth, Lucas (1988) shifts the attention to human capital spillovers and thereby ties information and informational spillovers to individuals. He also emphasizes the role of cities in facilitating informational spillovers. In doing so, he echoes Jane Jacobs's (1970) argument that cities act as a catalyst for exchange of information and ideas. Krugman (1991) contributes to underlining the context of the activities that generate and facilitate agglomeration and spillovers. Finally, Rauch (1993) puts focus on the local nature of knowledge spillovers and treats it like an urban amenity that can be described by wage and rent gradients. In the development of these theories, information goes from being intangible to being embodied in people and locally anchored in geography. This further implies that external flows of information are subjected to the constraints and frictions of space, time and human interaction. This line of thought is also developed by Jones (1997, 1999, 2005) who brings together

[18] Strictly speaking, a state of high entropy approaches randomness, meaning it contains little information. Conversely, a state of low entropy is far from random, meaning it conveys some information about how it departs from randomness.

[19] Schrödinger's argument is that solids are necessary to maintain reduced entropy and thus information.

[20] By extension this also implies that knowledge and know-how is how people process information into physical order, which is consistent with Hidalgo's framework.

[21] Romer (2016) develops this assumption further by distinguishing between human capital and codified knowledge. His argument is that while codified knowledge is non-rivalrous, human capital is still rivalrous, as that the loop between these two must be taken into consideration. This resonates with how Hidalgo (2015) distinguishes between knowledge and know-how.

population, ideas and growth to motivate increasing returns to population, as well as by Jones and Romer (2010) who describe growth as a interaction between ideas, institutions, populations and human capital. As this development progresses, the role of cities in informational spillovers and information processing becomes increasingly pronounced.

There is an intuitive link between the emphasis on people, human capital and ideas in endogenous growth theory and the increasing returns to scale in agglomeration economies. Glaeser et al. (1992) is one of the early empirical studies to make this connection and emphasizing local knowledge spillovers:

> *"If geographical proximity facilitates transmission of ideas, then we should expect knowledge spillovers to be particularly important in cities. After all, intellectual breakthroughs must cross hallways and streets more easily than oceans and continents."*

There is still a piece missing to the puzzle at this point. Information is assumed to be embodied in physical order and in the knowledge and know-how of people. Bringing people together in large populations in dense cities seems to result in agglomeration externalities in the form of knowledge spillovers or external flows of information, i.e. increasing returns to scale that is believed to rise from the concentration of this embodied information, but how? Somehow, information has to be transferred between people and this transmission has to have some competitive advantage to having each individual acquiring knowledge or know-how on their own. Alfred Marshall (1890) holds that intellectual flows between individuals decline with geographical distance and that people learn from each other by living and working close together. Neffke (2009, p. 16) describes this type of informational spillovers or knowledge spillovers as a form of *social learning*:

> *"A phenomenon that is often suspected to be one of the mechanisms behind agglomeration externalities is the fact that people who live in the same city, in one way or another, learn from each other. At this point, it is important to realize that learning is usually not an entirely individual activity. Although in principle, we can learn on our own – for example, by reading books or conducting experiments – a large part of what we know has been learned by interacting with other people. In fact, this interacting, or social, learning works best if people meet face-to-face."*

The idea that cities can act as a form of learning platforms has been further explored both theoretically and empirically by several authors (e.g. Glaeser 1999, Glaeser and Maré 2001, Duranton and Puga 2001, Andersson et al 2013, Combes et al 2008, Roca and Puga 2017). Duranton and Puga (2001) introduce their model of "nursery cities" in which firms leverage diversified cities during their innovation phase and then re-locate to more specialized cities associated with lower production costs. Roca and Puga (2017) find that workers in big cities accumulate an urban wage premium over time, an indication that they have gained valuable experience, which persists if they leave the city.[22] Andersson et al (2013) find evidence that the accumulation of human capital seems most pronounced in work related to problem-solving and interaction with others.

These studies all add to the case that there are external flows of information within cities, facilitated by local interactions and conceptually motivated by learning. This further accentuates the need to take the characteristics and configurations of these interactions into consideration. Why will some people interact and others not? How is the transmission of knowledge or information affected by who´s interacting? Nooteboom (2000) approaches these issues by introducing the concept of *cognitive proximity* and *absorptive capacity* as a means to explain the distribution of interactions and content of exchanges:

> *"A trade-off needs to be made between cognitive distance, for the sake of novelty, and cognitive proximity, for the sake of efficient absorption. Information is useless if it is not new, but it is also useless if it is so new that it cannot be understood."*

It follows that not only will everyone not want to interact with everyone else, but the content of an interaction depends to some degree on the relatability between the interacting parties.[23] Following this line of argument, Boschma (2005) introduces a multi-level framework of proximities - *geographic, institutional, organizational, social and cognitive* – to illustrate how co-located firms can still be a world apart in terms of interacting with each other in other, non-geographical dimensions. In other

[22] There is a long-standing debate on whether observable urban wage premiums arise from spatial sorting of more productive people to larger cities or from agglomeration economies. For the purpose of this text, I focus on the indications that sorting does not fully explain the observed premium and thus there is some indication of a differentiated accumulation of human capital in cities of different sizes.

[23] Nooteboom et al (2007) develop the model by trying to determining the optimal cognitive distance between firms engaged in technology-based cooperation.

words, learning as it is used here is not so much a question of frictionless transmission as it is an information processing activity.

Provided that interactions are associated to informational spillovers or learning between people, a naive assumption would be that more interactions will always generate more spillovers and, aggregated together, increased urban growth. Adding firm- or individual-level constraints in the form of cognitive distance raises the question of whether the relationship between interactions and positive externalities is simply positive and linear – more interaction, more productivity, innovation or growth – or if it is more complicated.

Intuitively, if interactions facilitate the flow of information between people and this in turn contributes to generating new ideas, more interactions should always be better. Accordingly, the ideal interaction system would be one in which everyone is interconnected with and interacting with everyone else.[24] However, this puts significant constraints on the system, and in particular on the individual who has to invest time and effort to interact with everyone else and also has to learn from all these interactions – to process the entire city's worth of embodied information. This is both work-intensive and time-consuming. Simon (1971) illustratively notes that if the amount of information grows, then something else must become scarce, namely attention. He makes the argument that such a system is unlikely to manifest on its own because of its evolutionary draw-backs compared to a hierarchical system structure (Simon 1982, p. 108):

> *"Suppose that complex systems have had to evolve (as they have) from simpler components. The time required for the evolution of a system of n parts, where n is large, will be very long, and will grow exponentially with n, if all n components have to come together simultaneously. However, if the elementary components can combine into small, stable subsystems, and small sets of those subsystems into larger systems, and so on, then the expected time of evolution for the entire system will grow only with log n. Hence hierarchical systems have an immense evolutionary advantage over those that are not hierarchical, and we may expect that almost all of the large systems will have hierarchical structure - as they do."*

The hierarchical system structure corresponds to the spontaneous order and self-organization described in the previous section. Translated to interactions between individuals within a city, what Simon's argument implies is that interactions should

[24] This is what in network terminology is referred to as a fully meshed network.

be expected to form social subsystems within subsystems of the city where the smallest components also hold the interactions that occur with the highest frequency, moving upward in the hierarchy to the interactions with the lowest frequencies. It echoes how social networks in cities are connected but not fully interconnected, i.e. everyone does not know everyone else in a big city.[25]

The idea of an hierarchical interaction structure holds important implications for informational spillovers in cities. First, it is not the number of potential interactions in a city, i.e. its population size, alone that determines the magnitude of its agglomeration externalities. It is also the configuration and distribution of these interactions. Second, the interactions that do not happen may be as important to what makes a place urban as those that do happen. This is because the hierarchical system allows information to be aggregated bottom up in a way that suggests that each individual can be exposed to more information than their number of interactions would suggest in a smaller system. Batty (2013, p. 17) hold that the number of realized interactions within a city is significantly smaller than the number of potential interactions. This may indeed be due to constraints, but it may at the same time also be an indication that interactions are ordered in an hierarchical way. The implications and possibilities of hierarchical interaction structures are explored in Paper 1 in this thesis, where a theoretical model is presented to link together empirical evidence on localized agglomeration externalities within cities with evidence of city-wide productivity gains scaling with city size.

Similarly, Hidalgo (2015, p. 78-108) defines the maximum knowledge and know-how that can be carried by a person (*personbyte*) and collectively by the network of people that makes up a firm (*firmbyte*). Volumes of knowledge that exceed the personbyte must be distributed across networks of people and volumes that exceed the firmbyte will be distributed across networks of firms, or under slightly different organizational principles the networks that cities consist of.[26] The result is a hierarchical system in which the separation between levels depend on the personbyte and the firmbyte. Hidalgo's conceptual framework explains the division of labor predicted by Adam Smith (1776), but he also elaborates on it by providing a motivation for "why industrial complexes of that size emerged to manufacture cars but not to make pins". The volume of knowledge required to build a car is far bigger

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[25] Schläpfer et al (2014) investigated cell phone data for Portuguese cities and found that both the call volume and the number of contacts rose with city size, but also that the degree of triadic closure, i.e. the number of your friends who also know each other, remained fairly constant. In other words, in a large city, people choose their own villages.

[26] Similar arguments about constraints have for instance been formulated by Dunbar (1992) about the number of meaningful relationships any individual can maintain simultaneously.

than that required to make a pin, and so the division of car-manufacturing will be greater than that for pin-making.

The interactions between subsystems beyond the most elementary level are less frequent, but just as important in conveying information across the system. The perhaps most well-known example of this is Granovetter's (1973) illustration of how links between individuals with few friends in common can play an important role in getting information about new job opportunities. The argument Granovetter makes is that people with large proportions of their friends in common form close-knit groups that already share all information, while the non-overlapping "weak" ties tap into other social groups that may provide new information. Hence the phrase "the strength of weak ties". Hollis (2013, p. 26) proclaims that "The city is built from weak links; it is these moments of human contact that act like electricity for the city."

Paper 4 in this thesis formulates a conceptual framework to deal with different types of interactions within cities and how they relate to information flows and the forming of social capital. Within the proposed framework, interactions are grouped based on their frequency and whether they are direct or indirect. Frequent and direct interactions characterize close friendships, family or co-workers you meet on a daily basis. Infrequent direct contacts correspond to distant friends, acquaintances or perhaps co-workers from other parts of the firm. Indirect contacts correspond to people you do not actively maintain a relationship with. These relations are rather a part of the context or of a specific place. Indirect frequent interactions might be the people who frequent the same coffee shop every morning, or neighbors who recognize and greet each other but who do not know each others' names. Indirect and infrequent interactions are a wider group of people you share the city with. People who bump into each other in the street, who gravitate towards the same parts of the city or belong to the same sub culture but who cannot pick each other out from a crowd.

All of these interactions contribute to the flow of information within a city, but in very different ways. While indirect and infrequent interactions are unlikely to spread detailed knowledge about quantum physics, they may well be a force to be reckoned with when it comes to spreading fashion trends, attitudes or norms. This speaks not only to the fact that the forming of social capital in cities is qualitatively different from that in rural communities, but also that cities make up complex social systems of interdependent interactions that constitute a form of collective information processing. The conceptual model is then matched against empirical evidence that the density of entrepreneurship in a square-kilometer neighborhood predicts the level of future entrepreneurship in that neighborhood. This is consistent with the idea that localized indirect interactions can promote inspiration or imitation, in this case resulting in the spread of entrepreneurship.

Furthermore, a hierarchical structure of interactions will also exhibit changes over time. For one thing, the information being processed within each layer of the structure and in each cluster interactions will change over time. Information is processed in cycles. This corresponds with what West (2017, p. 13) refers to as cities' social metabolic rate. It also echoes Mumford's description of the first cities as periodical meeting places, but extends it to a nested structure of meeting places

3.5 Evolution and adaptation

At face value cities, for all their dynamics and vibrant urban life, appear to be time-invariant. Any city has its patterns of routines, ranging from morning traffic jams to lunch hour to nightlife. Bourbon Street in New Orleans will always light up the evening with warm lights between the bars and restaurants, just as Kungsträdgården in central Stockholm will always gather a mix of sun-deprived Swedes and tourists for the cherry blossom in the spring and Times Square in New York City will never be empty in New Years eve. It is tempting to think of cities as clockworks – always in motion but never changing. Yet, a closer look at the internal order of cities and the external flows of information that permeates them tells another story. Beyond the bricks and mortar, cities are interactions, networks and flows (Batty 2013). Add to this that people and firms move in and out, relationships are formed and broken up, people switch jobs, industries come and go and new technologies are developed. Put differently, cities change in response to both internal and external forces.

With this in mind, cities appear to be the very opposite of static systems. They are shaped by and adapt to their history as well as changes in the world around them. This adaptation is not just the outcome of policy making, but of a bottom-up aggregation of individual but interdependent interactions and decisions. The resulting development reflects the varying timescales described in section 3.3, and together with the self-organizing hierarchical interactions structures described in previous section it may help to answer how cities can both change rapidly at the level of social interactions and very slowly at the level of built environment, economy and culture. Individuals or even firms may come and go but the modular structure they are or used to be part of persists, leaving a large city seemingly unmoved. Conversely, large, structural changes in the economy may arguably affect these different layers of the city's development differently. All of this describes an evolutionary process driven by co-evolution between the elements that make up the system and its resilience.

There is a a growing branch of economic geography, evolutionary economic geography (EEG), that employs the conceptual toolbox from evolution and evolutionary economics to address this type of issues. Boschma and Frenken (2006) frame the departure point for EEG with respect to three key issues they identify in economic geography: formal modelling, the of assumption of rational agents and the temporal dimension of the analysis. EEG, they argue, bridge a gap between two strands in economic geography literature that stress on the one hand the formalized quantitative analysis of utility-maximizing actors in a market place and on the other hand the role of qualitative institutions and actors with bounded rationality.[27] To this mix, EEG adds a temporal dimension to accentuate the role of history, path-dependency and irreversibility in regional development. Boschma and Martin (2010, p. 6-7) describe the research framework as a mix between generalized Darwinism, path-dependency theory and complexity theory. As part of the fundamental research agenda for an evolutionary economic geography, they list questions concerning the spatiality of economic novelty, the emergence of spatial structures from the micro-behaviors of economic agents, and the self-organization of the economic landscape.[28] These lines of inquiry mirror the questions of agglomeration economies, the internal order of cities and the flows and processing of information raised in the previous sections, but casts them in a context driven mainly by Darwinian metaphors.

Generalized Darwinism has made up the main stream in EEG, building on evolutionary economics and the adoption of a metaphorical framework including variety, selection and evolution (Nelson and Winter 2009). The principle assumption is that firms take on the role of species and harbor a set of routines that act as their genes. Firms actively search for new routines to increase their fitness in the selection process that is market competition.[29] In the geographical adoption of this framework, there is a growing body of empirical evidence on *related and unrelated variety* which draws on the non-geographical distance between firms based on their industry codes, technologies or the skills of their workers (Frenken

[27] What they refer to is New Economic Geography (or in their phrasing Neoclassical Economic Geography) and Institutional Economic Geography.
[28] In this, they echo Boschma and Martin (2007)
[29] Boschma and Martin (2010) hold that there is a risk of "a plethora of self-declared approaches" when metaphors are brought from one body of scientific work into another before there is a coherent theoretical framework developed for the new context.

et al 2007, Neffke 2009, Boschma et al 2014, Balland et al 2015, Neffke and Henning 2013). The different types of relatedness measures differ in substantial ways. Industry codes are based on old registers constructed from perceived relatedness at a prior point in time and may not correspond well to technological development like digitization or convergences between industries. Technological relatedness relies on the ideas that technological development follows an evolutionary path where current technologies are combined in new ways into new technologies. As such it is wider in context than the industry codes, but more closely tied to the activities going on inside the firms. Skill-relatedness describes the composition of human capital in firms and how workers move between firms. Apart from inferring the activities within the firms from the type of human capital they are willing to pay for, this also potentially opens for locally bound relatedness-measures within regions that could shed light on the locality, path-dependence and networks of regional economies. The mix of related and unrelated variety measures build on the concept of cognitive proximity and Nooteboom's (2000; et al 2007) emphasis on exchanges needing to contain new information, but not too new to relate to. This line of research lends itself to comparison with the studies on agglomeration economies and the balance between diversity- and specialization-related externalities raised in section 3.2. The relatedness literature has also been expanded to investigate and make predictions about how regions and cities can diversify into new related industries (Neffke et al 2011, Boschma et al 2014, Balland et al 2015).

There are several important limitations to the use of generalized Darwinism. First, Darwinian evolutionary theory was formulated to describe development ex post, and not to determine it ex ante. Thus, there is an inherent paradox associated with attempting to employ this type of metaphorical framework to predict natural selection, i.e. regional economic development. Second, generalized Darwinism covers only a special case of a wide variety of evolutionary dynamics. This is aptly illustrated with the conceptual tool *Darwinian spaces* introduced by Godfrey-Smith (2009). A Darwinian space is an equilateral cube of length 1. Each dimension of the cube is ascribed one of several possible features associated with evolutionary processes, allowing for "more or less" comparisons along three feature dimensions. For example, Godfrey-Smith suggests a cube spanning (1) fidelity of heredity, (2) dependence of fitness differences on intrinsic properties, and (3) smoothness of the fitness landscape. While evolution by natural selection is generally described by hereditary variations within a population that causes differences in reproduction it is clear that changing any of the features that span this space will yield a very different but still evolutionary process.

Dennett (2017, p. 148) elaborates on the concept and applies Darwinian spaces to cultural evolution, which more closely resembles the evolutionary approach taken to study regional economies. One of Dennett's examples spans the three dimensions (1) comprehension, (2) bottom-up vs. top-down, and (3) random vs. directed search. While a bottom-up process guided by random search without comprehension is surely Darwinian, can the same be said for a top-down process guided by directed search and high level of comprehension? Dennett instead calls this an unachievable state of intelligent design. If the objective is to study the evolution of firms within a regional economy, the individual firms will be driven by directed search, they will have some comprehension (although perhaps not full comprehension, just as they would not be considered to have full information in economic or game-theoretic terms). In addition, each firm is largely governed top-down, compared to the market where there is a stronger bottom-up component, meaning it matters whether we are talking about the evolution of firms or the evolution of the regional economy. Third, Godfrey-Smith (2009) also introduces the concept of *de-Darwinization*, describing a trajectory away from a paradigmatic Darwinian evolutionary process – evolution of evolutionary processes. The idea that the underlying process being studied may change over time – even over very long time scales – challenges the idea of applying a generalized metaphorical framework to study evolution in contemporary economies. The apparent risk is that the fitting of the framework obscures the particularities of the evolution going on. Complexity science provides an alternative approach to investigate evolutionary processes.

Complexity is the least explored component of the theoretical framework underpinning evolutionary economic geography (Boschma and Martin 2010). There are significant differences between the approaches taken in complexity science and in generalized Darwinism, and by extension also path dependency theory. First, while complexity must be either assumed or defined and explained within generalized Darwinism, evolutionary processes and irreversibility follow directly from the basic assumptions about interdependent interactions made for complex adaptive systems. It is not evident that evolution leads to increased complexity, and it may depend on what type evolutionary process is considered. On the other hand, complex adaptive systems always imply some form of evolutionary process, even though it is not predetermined what type. From this point of view, complex adaptive system theory may provide a better foundation for studying evolutionary processes in regional or urban economies without metaphorical limitation, especially since it accommodates several types of evolutionary dynamics. Furthermore, while general Darwinism have been employed to identify and explain micro- or meso-level mechanisms, i.e. some type of selection process, based on macro-level outcomes, complexity science works in reverse and aims to identify and explain macro-level system features that arise from distributed but interdependent activities. In other words, complexity theory is primarily concerned with self-organization and the spontaneous order or emergent behavior it produces, not with predicting the particular selection processes it may contain or their outcomes.

If related properly to each other, evolutionary processes and complex adaptive systems complement each other. Complexity provides a framework to describe and study the structural relations of systems. Evolutionary processes provides a framework to investigate micro- and meso-level behavior within such systems. However, generalized Darwinism on it own could also at its worse be reduced to a conceptual or metaphorical framework that is applied ad-hoc (Essletzbichler and Rigby 2010). Macro-level system properties derived from complexity and adaptability can provide insights on the character and variation of evolutionary processes within that system. As Rose (2016, p. 6) notes in favor of a complexity approach to cities:

> *"When Charles Darwin added the phrase 'the survival of the fittest' to his fifth edition of The Origin of the Species, at the suggestion of the economist Herbert Spenser, by 'fittest' he didn't mean 'strongest'; he was referring to those species that fit together best."*

This resonates strongly with the intellectual motivation behind the empirical research on related and unrelated variety.

Martin and Sunley (2007) state that complexity theory, in particular self-organization, holds the potential to make valuable contributions to the construction of evolutionary economic geography. However, they oppose the line of research that focuses solely on simulation and agent-based models and calls for a different approach:

> *"[We need] a more philosophically inclined social-ontological approach. What precisely does it mean to talk about the economic landscape as a complex system? In what sense is the economic landscape a meaningful complex system to which the concepts of complexity thinking can be meaningfully applied?[...]*
>
> *We take the view that if 'the economy' is indeed a complex system, its complexity arises in large parts precisely because it is spatially distributed and spatially embeddded."*

This calls for an approach to complexity that links together the features of density and agglomeration economies with the internal order of cities, information flows and interactions between people and the evolutionary approach to cities and economic geography.

Martin and Sunley (2007) base their discussion on a comparison between evolutionary economic geography and complexity economics.[30] In this, they raise five issues: 1) If cities or regions are self-organizing, are they also *autopoetic* in the sense that they reproduce the components they are made up of, 2) if control is distributed and decentralized in the system, then how can self-organizing systems account for power structures, 3) it is hard to identify endogenous effects in a city or region where boundaries are hard to identify, 4) what is the relationship between self-organization and order, and 5) what is the relation between self-organization and adaptation. It is a worth-while task to reply briefly on these issues in order to to begin to carve out the contours of an alternative and coherent complexity approach to cities.

First, autopoiesis is related more to the systems adaptation than to its complexity. While the two are overlapping, the way a complex system adapts may differ, meaning its autopoetic nature is not likely to be binary. Self-organization in complex adaptive systems is intimately related to the openness of the system, meaning the order does not specify individual parts to be constant. If self-organization is maintained over time in an open system like a city where people and firms move in and out, then it is the order, and not the parts, that are reproduced. In fact, it is not even the links between the specific parts, but the structural pattern that is self-organized (Batty 2013). Self-organization is the unintended aggregated outcome of many individual, intentional and interdependent decisions (Miller 2016). This is what makes up the internal order of cities and the hierarchical structures of informational spillovers discussed earlier. The intentional activities may change, while leaving the unintentional outcome intact.

Second, the decentralized distribution of control in self-organized systems does not imply an even distribution of control. On the contrary, self-organization is associated with power law distributions that exhibit exponential differences between parts. In addition, power related to intentional activities, organizations or institutions may not translate fully into power in a self-organized system. That is, someone with

[30] Since complexity economics is an adoption of complexity theory (or parts of it) to economics, the comparison suffers in some part because there is no distinction between what is general complexity theory and what is the interpretation done in the framing of a specific line of complexity economics (e.g. Beinhocker 2006).

little formalized power may have huge influence in a specific context, which also echoes what we should expect from reality.

Third, it is indeed hard to isolate endogenous effects in a complex adaptive system. This is one of the drawbacks of complex adaptive system analysis – it is not geared towards the identification of micro-level mechanisms and predictions based on such mechanisms, but towards the macro-level features of the system (Miller and Page 2007). For instance, micro-level mechanisms may provide an explanation for why a group of individuals interact more with each other than with others, but complexity can describe how and why multiple occurrences of such clustering leads to the formation of a hierarchical system that improves the collective processing of information and informational spillovers.

Fourth and fifth, self-organization implies grown or spontaneous order as an outcome of individual elements interacting with each other. From a complexity perspective, a city can be said to have both the made order (taxis) of for instance institutions and firms, and the grown order (kosmos) of how individuals interact within the system with respect to the structures of made order (Hayek 2013). It follows that adaptation on the system level is the outcome of adaptation at the individual level (Page 2010, p. 25). Here Martin and Sunley (2007) bring up the issue of explaining *selection* from an evolutionary perspective. However, the emergence of order in a system, whether natural or social, may not have to be the outcome of distinguishable selection but can for instance come from how parts of the system fit together, echoing the quote from Rose above (Kauffman 1993).[31] That is, selection is not the same as adaptation. Furthermore, selection in a biological system of, let's say fish, differs quite significantly from the market selection that is the outcome of interdependent but intentional strategies between individuals and firms. For one, the decisions made by the latter are not necessarily confined geographically in a globalized and digitized economy.

Against this backdrop, we can now turn to complexity and complex adaptive systems in their own right.

[31] Forster (2005) approaches these issues by dividing complex systems into four hierarchical orders of complexity.

3.6 Complex adaptive systems

In the words of Page (2010, p. 32), "complexity lies between order and randomness". As simplistic as it may sound, this provides a fundamental starting point for defining a complex approach to cities. Imagine a busy street in a vibrant city like Paris, Shanghai or San Francisco in the morning. At first sight the mix of pedestrians, cars, bicycles, busses, trains and – not to forget – coffee mugs appears completely haphazard. A closer look, however, reveals that each individual has their own plan. It might not be a very well thought-through plan, like trying to board the subway before the disembarking passengers have made it off the train, but it is still a plan. People do not move around the city and interact randomly with strangers like particles in a gas. On the other hand, they do not follow the same plan either. If they had, it would have been a small thing to agree to let people exit the subway train before getting on it. In other words, cities are ordered in the sense that they are not random, and disordered in the sense that they do not follow a centralized plan – they are self-organized and make up a *complex adaptive system*.

There is an important point to be made in distinguishing between complexity and adaptation, even though they are virtually inseparable in most real examples of social systems, and especially cities. Complexity can crudely be thought of as the interconnectedness and interdependence between parts of a system and the way in which these systems can "order themselves", i.e. self-organize (Colander and Kupers 2014, p. 46-48). Even if the system is not adaptable it may be dynamic in the sense that parts interact with each other and self-organize over time. What adaptability adds to the mix is that the parts can change the way they interact with each other as a response to the rest of the system or external stimuli (Miller and Page 2007). This is often referred to interchangeably as complex *evolutionary* systems or complex *adaptive* systems. This thesis deals exclusively with complex adaptive systems.

The idea of complexity, if not formulated in those terms, is traced back to Adam Smiths' (1776) description of the *invisible hand* – "a force that leads self-interested traders to unintentional, socially desirable outcomes" (Miller 2016, p. 4). Similarly, Schelling (1969, 1971) demonstrates how micro-level preferences can generate unintended and negative macro-level outcomes, in this case in the shape of segregation. This width of potential impacts makes the understanding of complex adaptive systems crucial to social systems like cities or regions.

Three decades ago, Lloyd (1988) started counting and ended up with some forty definitions of complexity. Today, there is still no definitive definition of complexity or complex adaptive systems, but this may not be so much of a lack of coherence as a multitude of approaches to the subject (Miller and Page 2007, Mitchell 2009, Page 2010). It puts demand, however, on any complexity framework to be satisfyingly defined for the task it is employed for. For this thesis, I will draw mostly on the contemporary literature in complexity theory.[32]

Complexity can be conceptualized either as a binary property or as a quantitative measure, i.e. something can be more or less complex. When measured, complexity is commonly defined in some manner by the resources required to describe the system, its *description length*. For instance, the Kolmogorov complexity of a sequence of numbers is the minimum length required to write a program that produces that same sequence. An immediate problem with this measure is that a random sequence of numbers can be either infinitely complex or trivial ("produce random numbers"). Other attempts have been made, for instance to focus on the description of regularities (effective complexity) or the number of steps to reproduce the sequence (logical depth) (Page 2010). In this thesis, complexity is treated as a measurable quantity, but it is not explicitly measured. The reason for this is that it allows for a combination of complexity and *emergence* (Page 2010, p. 25). Emergence is broadly defined as the higher-order patterns and features that is generated by the interactions between elements in a system. If complexity is treated as a property, then emergence must be said to vary between different systems, whereas if complexity can differ between more or less complex systems, then structural differences in emergence can be assumed to be inherent to the level of complexity.

Furthermore, what is complex must also be distinguished from what is complicated. A system can be complicated without being complex, if its elements remain largely independent from each other. Conversely, a system can be complex without being complicated, if the elements follow a set of simple rules but act interdependent of each other. Miller and Page (2007, p. 9) illustrate the difference between complication and complexity with the following example:

> *"Removing a seat from a car makes it less complicated, removing the timing belt makes it less complex."*

[32] In (evolutionary) economic geography, the literature on complexity economics has made an impression of the interpretation and treatment of complexity. In order to provide a coherent and straight-forward conceptual framework, I have kept to more general literature so as to not be limited by previous adaptions made to accommodate economics rather than geography.

While complicated systems can be reduced to their parts and studied individually, complex systems are – as the popular phrase goes – *more than the sum of their parts*. This expression, however, may be a bit misguiding because it implies that complex systems must be studied as a whole. An alternative is to say that the whole is *different* from the sum of the parts, i.e. that something but not everything can be learned about a system by studying its parts (Mitchell 2009, p. 40-56).[33]

Putting complexity into a systems theory will require some principle description of how the parts relate to each other and to the whole. Miller (2016) notes that "complexity arises in systems of interacting agents" and that "in physics, individual atoms organize into magnets, in biology, cells organize into organisms, and in economics, traders organize into markets". Page (2010) defines a *complex system* as the interactions between a set of diverse entities in a network or contact structure who follow a set of rules and whose interactions are interdependent of each other.[34] In addition, Page emphasizes that if the individuals can adapt the rules they follow, then the system becomes a *complex adaptive system*. In other words, the adaptation is itself an outcome of aggregated adjustments, an emergent response. This implies that they experience positive feedback loops, or positive reinforcement.

A system's speed of change can be related to its diversity. Homogenous systems in which all entities act in the same way are more likely to change quickly and to go into oscillations, while heterogeneous systems go through slower change (Miller 2016, p. 10). Miller and Page (2007, p.) illustrate the role of heterogeneity with an example of bees:

> *"For honey bees to reproduce and grow, they must maintain the temperature of their hive in a fairly narrow range via some unusual behavioral mechanisms. When the hive gets too cold, bees huddle together, buzz their wings, and heat it up. When the hive gets to hot, bees spread out, fan their wings, and cool things down. Each individual bee's temperature threshold for huddling and fanning are tied to a genetically linked trait. Thus, genetically similar bees all feel a chill at the same temperature and begin to huddle [...]*
> *Hives that lack genetic diversity in this trait experience unusually large fluctuations in internal temperatures. In these hives, when the temperature passes the cold threshold, all the bees become too cold at the same time and*

[33] This resonates with Andersson's (1972) statement that "more is different".

[34] Miller (2016, p. 30) further agues that there is a distinction between complex systems where simple entities generate complex emergent outcomes and those where complex interactions generate simple emergent outcomes. Even though this distinction has it merits and deserves further discussion, this is outside the scope of this text.

huddle together. This causes a rapid rise in temperature and soon the hive overheats, causing all the bees to scatter in an over ambitious attempt to bring down the temperature."

Relating this back to the internal order of cities and social interactions, the different time scales described and the balance between made order (taxis) and grown order (kosmos) are implicitly associated to different degrees of diversity in their degrees of freedom to adapt, i.e. the ways in which they can change. The change in built environment is slower and more strictly governed by regulation, while changes in social interactions and networks of relationships change quickly and exhibit a high degree of diversity in how they change. The adaptability of firms lies somewhere in between, being more strictly controlled by regulation than social interactions but less so than built environment. In other words, the level of regulation and speed of change also makes up a form of vertical diversity in adaptability.

Complex adaptive systems are generally considered to be open, far-from-equilibrium systems with positive feedback loops, as opposed to closed equilibrium systems governed by negative feedback (Batty 2017).[35] In addition, complexity, or more precisely the growth of complexity, can be related to entropy and by extension to the growth of information. Hidalgo (2015, p. xx) argues that it is the simultaneous increase of complexity and information that marks the development of everything from life to modern economies:

"It is the growth of information that unifies the emergence of life with the growth of economies, and the emergence of complexity with the origins of wealth[...]

Yet the growth of information is uneven, not just in the universe but on our planet. It takes place in pockets with the capacity to beget and store information. Cities, firms, and teams are the embodiment of the pockets where our species accumulate the capacity to produce information."

[35] This does not, however, mean that complex systems cannot attain equilibrium (Page 2011), but that they cannot be assumed to be in equilibrium. The motivation for defining them as open builds on the entropy argument, i.e. that unless they were open entropy would rise and complexity would decline over time. Poistive feedback relates to the interdepedency of interacting entities, in combination with the openness of the system, which can generate cascade effects.

Another hallmark of complex adaptive systems is that they exhibit some degree of self-similarity or self-affinity, i.e. a fractal pattern that is repeated proportionately at different scales within the system (Mandelbrot 1983). Fractals are intuitively associated to geometric forms, but self-similarity can just as well be expressed in social links in a network or the interaction intensity between parts of a system.[36] Self-similarity in turn describes patterns associated with self-organizing and hierarchical systems as described in previous sections (Simon 1982). That is, complex adaptive systems are assumed to form hierarchical contact structures through self-organization.

The idea of cities as complex systems dates back to Jane Jacob's (1961) description of cities as "problems in organized complexity", but it is only during the last two decades this ambition has been translated into models of systems that evolve and emerge from bottom-up (Batty 2008). Bettencourt (2013a) remarks that "the challenge of defining the kind of a problem a city is goes well beyond the principled rejection of the urban renewal" and that "[what] lives on as a challenge is the creation of new and better reconceptualization of cities as complex adaptive systems".

During the last decade, a growing number of studies have conducted to derive and predict exponentially increasing returns to scale, *superlinear scaling*, of social and economic output factors with city size, so called *urban scaling analysis* (e.g. Bettencourt and West 2010; Batty 2008).[37] A growing body of empirical studies have found superlinear scaling for a variety of factors that are associated with interactions between people including total wages, GDP, patents, cellphone traffic and social ties, crime and walking pace (Bettencourt et al 2007a; Bettencourt et al 2007b; Schläpfer et al 2014).[38]

Bettencourt (2013b) conceptualizes cities as "integrated social networks embedded in space and time" and states that their socioeconomic output is proportional to the number of realized social interactions per unit time. In a parallel initiative, Batty (2013, p. 39) theorize that as cities get bigger, "their average real income (and wealth) increases more than proportionately, with positive nonlinearity, with their population". These accounts both relate to the empirical regularities found between cities of different sizes in studies of agglomeration economies, but put them into a

[36] Such relationships are also called scale-free or scale-invariant.
[37] Bettencourt and West even refer to the approach as a "unified theory of urban living"
[38] These studies also report decreasing returns to scale for infrastructure per capita and other indicators that are associated with sharing of (public) resources.

general "law-like" setting where population size is used to predict a number of economic and social factors for that city.

Paper 2 in this thesis employs the scaling framework to a disaggregated within-city spatial scale and substitutes employment density for population size as a proxy of interactions. The main finding of the paper is that similar scaling results are found on a square kilometer "neighborhood level" within three Swedish cities, suggesting that the fractal nature of social interaction is somehow related not only to productivity gains related to city size but also to localized agglomeration externalities like informational and knowledge spillovers.

There may be more to urban scaling and externalities than the number of realized interactions and quantity of socioeconomic output form a linear positive relationship. The empirical findings in the urban scaling literature suggest that outputs rise by about 15 percent with a doubling in population size. The number of potential interactions however scales as the square of the population. Making the simplifying assumption that each realized interaction contributes equally to socioeconomic outputs and urban growth, the difference between the rise in potential interactions and reported output suggests that interactions do not rise proportionately, and that it may not just be the number of interactions but their configuration that matters to the total output.[39] This underlines the relevance of exploring the link between agglomeration externalities and the hierarchical structure of complex adaptive systems.

Batty (2013) brings the toolbox of complexity and complex adaptive systems inside the city. In doing so, he stresses the relation between the physical and the social city and states that:

> *"[Cities] must now be looked at as constellations of interactions, communications, relations, flows, and networks, rather than locations, [...] and location is, in effect, a synthesis of interactions."*

This resonates with empirical findings suggesting that although different, social and geographical distances tend to coincide partially (Feldman and Tilly 1960, Hipp and Perrin 2009). Batty describes cities as patterns of social and economic activities that arise from the spatial and temporal distribution of interactions, networks and flows.

[39] Schläpfer et al (2014) report findings suggesting that the number and frequency of social contacts rise with city size, which would suggest again that the relation between interactions, interaction structures and agrgegated externalities is more complex.

Drawing on the work of Herbert Simon, he defines the city as a hierarchical system but stresses that the subsystems should be thought of as mutually exclusive geographical areas as in the case in zoning regulation. Instead, the hierarchy is defined as one between overlapping social subsystems anchored in space. In this, he echoes Alexander (1968) who argued that the hierarchical system of a city is not a tree, but a semi-lattice.[40]

In line with Batty's emphasis on the link between interactions and locations, Portugali (2006) suggests that a complex systems approach can bridge the divide between *space,* which has been prevalent in quantitative sciences, and *place*, which has been dominant in qualitative sciences. While space entails the distance between things, place emphasizes locality. Boschma and Martin (2010, p. 7) similarly stress the role of location in evolutionary economic geography:

> *"For the economic landscape is not just the passive outcome or by-product of the process of economic evolution, but a conditioning influence on that process. Economic transformation proceeds differently in different places, and the mechanisms involved neither originate nor operate evenly across space."*

This is equally true for different places within cities as it is for different cities or regions. Evert city has a set of places that are characterized by or infused with particular social activities and traits. Picking a location to open a restaurant or a shop is not merely a matter of distance, but of how and where people concentrate to socialize or to shop. The self-organized hierarchical system of social interactions and activities within a city is anchored in places and fuels an interaction across the different speeds of the city's adaptation.

[40] Alexander also stated that overlaps are not simply planned and balanced, writing that "a garbage can is full of overlap. To have structure, you must have the right overlap".

3.7 Summary of papers

Each paper included in this thesis explores and investigates the implications of inherent patterns of complexity in agglomeration economies on a within-city scale. Together, and combined with the theoretical framing presented in the previous sections, they contribute to sketching a wider picture of how complex adaptive systems can be used to describe local interactions and agglomeration externalities within cities and dense environments.

Paper 1 makes a theoretical contribution by introducing a conceptual interaction model that links together empirical regularities associated to localized within-city agglomeration externalities and city-wide productivity gains that scale with city size. The model is based on the assumption that individuals process information through interactions and that they will on average behave as if they were trying to maximize the amount of new information they process while minimize the effort it takes them to do so. Their behavior is subject to physical constraints that penalize extensive transport and cognitive constraints that favor interactions between people who have something in common but still can exchange new information – remember Nooteboom's (2000) observation that "information is useless if it is not new, but it is also useless if it is so new that it cannot be understood." The model produces a hierarchical interaction structure that consists of components of individuals based on their interaction frequency which favors coordination in space to reduce transport costs, i.e. anchoring in places.

The model explains the occurrence of localized informational spillovers as the outcome of high-frequency interaction components anchored in specific locations, for instance sharing of professional knowledge in and around workplaces. When applied to a larger city, i.e. a larger population of individuals, the model predicts more specialized interaction components, which leads to a higher degree of information refinement per hierarchical layer in the interaction structure, i.e. that components produce a form of consensus information that is exchanged through the lower-frequency interactions at higher level of the structure. Consequently, the model explains productivity gains related to city size as the outcome of a division of information processing, mirroring the idea of specialization through division of labor, that allows individuals on average to process more new information per unit time in a large city compared to a small town.

An interesting consequence of the model is that the anchoring of interaction components in places contributes to making the interaction system more open-ended. That is, individuals without social ties to a specific interaction component can come in contact with it through the place it is anchored in. This will of course differ between private clubs of gatherings and wider public spaces.

The model in Paper 1 lays the foundation for an analytical framework by consolidating empirical regularities associated to agglomeration externalities and productivity gains at both neighborhood- and city-wide level with the theoretical framework related to complex adaptive systems and self-organizing hierarchical interaction structures. Furthermore, it suggests that cities facilitate a form of collective information processing in which individuals benefit not only from their own interactions but also those between others. Put differently, it is not only the share of the potential interactions between individuals being realized that matters to productivity gains, but also the structure of those interactions. In some sense, the interactions *not* being realized may play a just as important role as those that are in terms of the aggregated result. This collective information processing could be thought of as a form of collective learning, but also as a form of collective memory that contributes to the resilience of urban economies under the constraints of in- and outmigration of individuals and firms over time.

Paper 2 builds on this foundation by identifying within-city superlinear scaling in productivity gains related to employment density. The results in urban scaling analysis, that several measures of socioeconomic output increase exponentially with city size, are theoretically attributed to a rising number of realized interactions between individuals in larger cities. Along this line of argument, and provided that interactions are constrained in physical and social space, employment density should provide a corresponding proxy for social interactions on a intra-urban spatial scale. Against this backdrop, Paper 2 presents empirical results from three different regression models that capture the correlation between employment density and total wages on a neighborhood level in the three largest metropolitan regions in Sweden (Stockholm, Gothenburg and Malmö). Neighborhoods are defined as a grid of geocoded data from Statistics Sweden divided into exogenously determined cells of two different sizes ($250m^2$ and 1 km^2).

The first model is a simple OLS regression, which includes a control variable for the distance to the central business district (CBD). The results show strong superlinear scaling at both disaggregated levels. The OLS model is also run specifically for individuals with higher education, for individuals working in manufacturing and service sectors and for subdivisions of knowledge-intensive or less knowledge- intensive sectors, each in relation to the density of their sub category. The results suggest stronger scaling for individuals with university education or those employed in service sectors. This is consistent both with the empirical evidence of highly localized agglomeration externalities related to informational spillovers and knowledge spillovers and with the superlinear scaling found with respect to city size in inter-city comparisons.

The second model is a panel regression model with fixed neighborhood effects, meaning the results show how marginal increases in employment density (rather than just comparisons across neighborhoods) correlate with total wage. Again the results show strong superlinear scaling, but the effects are smaller than for the OLS model. The model is also tested for individuals with university education, and again the scaling exponent is higher for this group. While the results strengthen the case for within-city superlinear scaling with respect to employment density, the difference in effect also suggest that part of the effect may be related to place rather than simply to density. This would resonate with the idea that interactions may be anchored in places in a way that facilitates positive feedback effects.

The third model is a quantile regression model that correlates density to total wages separately for different quantiles of the neighborhood wage distribution. The results show that although all types of neighborhoods exhibit superlinear scaling, neighborhoods at the lower end of the aggregated wage distribution are associated with higher scaling exponents, i.e. they benefit more from increased density. This result is even stronger for individuals with university education. While this adds to the evidence that employment density generally promotes scaling in productivity gains, this also suggests that those with lower wages, whether they have a university education or not, benefit the most from working in dense environments. This implies that the increasing returns to density decrease at the higher end of the aggregated wage distribution. Conversely, it suggests that the scaling relationship, and its underlying externalities, benefit the lower end of the aggregated wage distribution the most. Put differently, if people learn from each other this may be an indication of the direction of such spillovers, people with lower wages appear to benefit more from working in dense environment, all else aside.

The collective results from Paper 2 strengthen the model presented in Paper 1 by empirically validating the existence of self-organization and scaling with respect to employment density on a within-city scale. Curiously, it seems that the results do not differ in magnitude between the cities investigated, implying no significant variation with respect to urban hierarchy. It also adds to the idea that interactions, specifically professional non-market interactions, are anchored in locations, in this case the neighborhood cell surrounding the workplace. The difference between the OLS and panel regression results suggest that other factors apart from density may also contribute to the scaling pattern.

Paper 3 moves from individual- to firm level analysis and elaborates on the micro-geographical distribution of firms within cities. The motivation for the paper is to test specialization-related externalities (MAR-externalities) against diversity-related externalities (urbanization- or Jacobs externalities) on two different spatial scales. While many previous empirical studies have matched them on city-wide scale only, the hypothesis presented here is that diverse urbanization economies may consist of neighborhood level clusters that reap the simultaneous benefits of specialization externalities. This paper is not cast in the complexity framework, but focuses exclusively on agglomeration economies and localized externalities. What makes it relevant to a complexity approach, however, is that it implicitly tests if there are productivity gains related to a structure of locally bound and specialized clusters, which corresponds to a firm-level geographically constrained version of the theoretical complex adaptive system model presented in Paper 1.

The empirical model is a panel regression that correlates total factor productivity (TFP) with specialization (within-industry employment) and diversity (between-industry employment) at neighborhood- and city-wide level respectively. Neighborhoods are defined by a geocoded grid of square-kilometer cells based on the same data material used in Paper 2. The city-wide level is defined by the local labor market region, which gives a functional definition of a metropolitan region. The model contains a wide array of control variables including firm, year, industry, and human capital fixed effects to account for unobserved heterogeneity among firms. In addition, an index of diversity measured by relative employment distribution in other industries, a so called Herfindahl-index, is included at the city-wide level of observation. This provides a measure not only about employment outside the own industry, but also how that employment is distributed across industries. Because of the focus being the specialization or diversity of employment, the model also includes controls for the influence of employment in the first order neighbor cells on the grid – that is, the cells that surround the observed cell. This way, a firm located at the edge of a cell, adjacent to another cell with very different metrics will not be “cut off” from that part of their immediate surroundings.

The results show significant and robust effects of both diversity and specialization at the neighborhood level, as well as corresponding significant and strong effects of the Herfindahl-index diversity measure at the city-wide level. Thus, specialization and diversity effects are not mutually exclusive. Further investigations suggest that local specialization effects remain positive and significant across industries although they vary in favor of for instance knowledge-intensive and high-tech industries. This is consistent with the idea that localized agglomeration externalities pertain especially to knowledge spillovers and informational spillovers. The finding that both specialization and diversity effects are positive at a neighborhood level also translates roughly into a general effect of employment density that corresponds to the findings in Paper 2. The main contribution of this paper to the thesis is to show that there are evidence of self-organization of productivity gains at a firm-level, consistent with specialized concentrations within a diverse urban economy. Put differently, the diversity of a sucessful urban economy may not be randomly distributed in space, but forms a pattern of specialized neighborhoods. This should not be mistaken for something that can be planned, but rather an expression of self-organization reflected in firm performance.

Paper 4 presents a conceptual model of different types of social interactions within cities and their relation to the forming of social capital. I will not go deeper into the literature on social capital because it is developed further in the paper and because it lies outside the scope of the kappa. The contribution of this paper lies instead in the interaction model it introduces and the empirical matching of this model to local density of entrepreneurship.

The model distinguishes between direct and indirect as well as frequent and infrequent interactions.[41] While direct interactions span the spectrum that is normally associated to bonding (frequent) and bridging (infrequent) social capital or close and distant relationships, indirect interactions span a corresponding spectrum that includes varying degrees of peer effects, neighborhood effects, imitation or inspiration. Such interactions are rare in a small town where everyone knows everyone else, but commonplace in a large city were many people do not know their neighbors.

The conceptual model is matched against empirical data showing that the neighborhood level density of entrepreneurs works as a predictor of future entrepreneurship, defined as workers leaving their employment to become entrepreneurs. Put differently, entrepreneurship seems to some degree to be contagious. The investigation is based on the same disaggregated and geocoded data from Statistics Sweden as the one used in papers 2 and 3. The result is consistent with the idea that an activity like entrepreneurship can be promoted by indirect interactions, in this case living in the same residential neighborhood as other entrepreneurs, that lead to inspiration or imitation of that behavior. For instance, if neighbors perceive that a local entrepreneur is doing well, they may be inspired to start their own venture either out of inspiration or jealousy.

[41] In the paper they are referred to as thick and thin to include both the time and the attention put into the interaction.

Paper 4 makes three significant contributions to the thesis. First, it illustrates one way in which interaction structures change not only quantitatively but also qualitatively moving from sparsely to densely populated areas. Second, it provides a case for how external information flows enable collective information processing, or social learning and memetic evolution as discussed in section 3.4 on information and interactions. Finally, it explores a variation of how external information flows are anchored in shared places, rather than limited to established social ties and networks. Empirically, the case presented broadens the category of places considered, from workplaces to residential neighborhoods. It could be argued that what people sharing a workplace neighborhood have in common differs significantly from what people living on the same street have in common.

3.8 Summary

At the beginning of this thesis I set out to explore and describe how local agglomeration externalities and informational spillovers may be described in terms of complex adaptive systems. Drawing on the combined results from the four papers combined with the theoretical work in chapter 3, I make a two-fold conclusion that responds to the research questions from chapter 1.5.

First, local interactions, as observed by agglomeration externalities, exhibit self-organization. Specifically, as shown in paper 2, localized productivity gains scale superlinearly with disaggregated variations in employment density. Furthermore, the results in paper 3 are consistent with the idea that firms exhibit productivity gains associated to local specialization within a diverse city. This corresponds to a hierarchical interaction structure, a characteristic of self-organizing systems. Second, paper 1 shows that complex adaptive system properties, particularly hierarchical structures of local interactions, are consistent with and can consolidate within-city agglomeration externalities and aggregated productivity gains related to city size. Together with the conceptual model of interactions specific to densely populated cities presented in paper 4, these conclusions speak to the idea that interactions change both qualitatively and quantitatively with increased population size and density.

What these conclusions mainly imply for both future research, and to some degree also policy making, is that even if the number of realized local interactions within a city seems to scale with its population size (e.g. Schläpfer et al 2014; West 2017), this may only be part of the story. The self-organizing structure of these interactions would also appear to contribute to the improved information processing capacity, or a division of information processing.

Chapter 4:
Concluding discussion

4.1 A coarse-grained theory

Building on the previous chapter, I start this concluding discussion by turning the table to sketch a model of what cities may look like and how they might work *assuming that they are complex adaptive systems* made up by local social interactions. This is a coarse-grained theory and a thought experiment based on what has been showed and deduced in the thesis.

- Social interactions self-organize into a structure consistent with an embedded hierarchy of components based on frequency of interactions and anchored in locations. High-frequency interactions form tightly knit components at the bottom of the hierarchy and are gradually bundled into larger modules connected by interactions of decreasing frequency moving up the hierarchy. This is the principle model explored in paper 1.

- Insomuch as social interactions give rise to informational spillovers that generate productivity gains and urban growth, a complex adaptive local interaction structure implies that more interactions or serendipitous encounters may not be what is driving growth. Even if interactions grow with city size, it may in fact be the structure they take that enables a more efficient form of collective learning through increased division of information processing with city size. This implies that unrealized interactions also hold a value in terms of productivity gains.

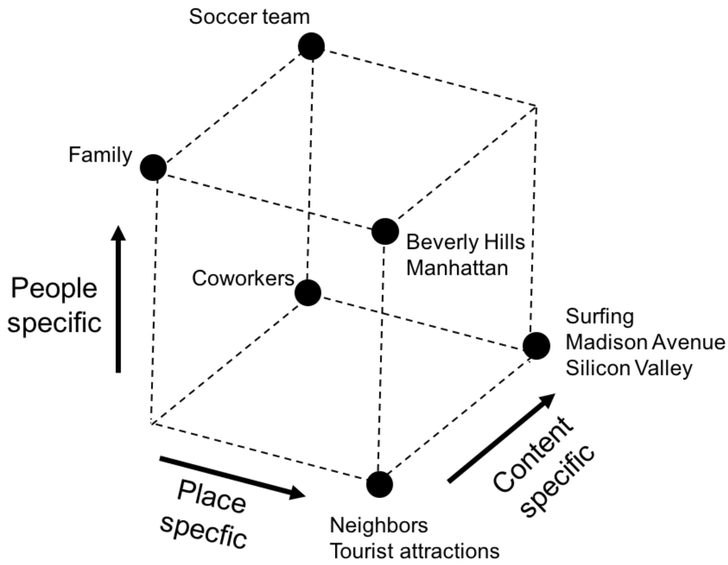
- The hierarchical structure enables a form of collective information processing or learning. Agglomeration externalities and informational spillovers are strongest at the bottom of the hierarchy were interactions are most frequent, explaining the empirical evidence of localized externalities consistent with learning and flows of information. Interaction components are not mutually exclusive divisions of the population or geography, but rather overlapping subsystems of both. High-frequency interactions can describe both direct interactions with friends or coworkers and indirect encounters with people who frequent the same coffee shop, consistent with the conceptual model in paper 4. These interactions are similar in frequency but differ in their content. The structure scales with population size by forming more specialized or niched components at the bottom of the hierarchy.

- The hierarchical self-organized interaction structure gives rise to scaling relations with respect to within-city variations in employment density, in line with the results from paper 2. In other words, the collective information processing or learning that generates productivity gains within a city is fractal in nature. It scales across spatial levels, from small to large neighborhoods and from small to large cities, tying into urban scaling analysis. In addition, the scaling relationship appears to enable a diffusion of productivity gains from the most productive to the least, consistent with a form of collective learning. This implies something about how social and economic activities are distributed across density within cities, but it also hints at the social-geographical composition of the city as such. Knowing that productivity gains follow a power law distribution with respect to density and neighborhoods, means that the is an inherent unevenness to urban economies that is likely to be reflected at both individual- and firm level.

- Adaptation within the local interaction structure to external as well as internal changes in the form of new information will happen gradually from the bottom (high-frequency interactions) to the top (low-frequency interactions). The way adaptation is propagated through the structure implies that it can be described in terms of cycles. This is perhaps best exemplified by trends in sub culture fashion or in popular restaurants but also topical trends within professional communities like marketing. Interaction components go through cycles in which they are either created, maintained, altered or destroyed. The process is repeated throughout the structure as higher-level structures adapt to the bottom level. In this way, interactions rearrange themselves in relation to new information. Essentially this means that a city can be described as a nested structure of cycles. This cyclical perspective quintessentially constitutes a form of social information metabolism within the city (West 2017, p. 13), i.e. the way in which people consume energy and resources in order to process information that by extension can lead to the generation of new ideas and innovations. This would in turn have implications for how cities go through structural changes in the economy, a way of mirroring Schumpeter's notion of creative destruction in local interaction structures as they adapt their collective information processing. A cyclical perspective also addresses the question of whether the system is autopoetic (Martin and Sunley 2007), i.e. if it reproduces it self, by shifting focus to *how* it reproduces itself through adaptation

- Defining exactly how interactions are anchored or situated in locations is all but impossible, but differences in how interactions are situated in locations must still be considered in some manner. The empirical results from the papers rely primarily on informational spillovers related to employment density and workplaces, with the exception of Paper 4 where residential neighborhoods are considered. Other types of interactions were considered in the theoretical framework in chapter 3. Workplaces are a good proxy for work-related interactions since these interactions are content-specific and likely to occur on average within a square kilometer neighborhood at any point in time. A rough categorization can be made by differentiating between interaction components based on what they depend most heavily on, or conversely what type of changes they are most sensitive to: the people engaging in the interaction, the place where the interactions happen or the content of the interactions. This categorization can be visualized with the same basic concept used to illustrate Darwinian spaces in section 3. 5, but in this case it shows interaction spaces (see Figure 4). While the repeated interactions within a family depend primarily on people (family members), interactions within a workplace depend mainly on the content (coworkers), and interactions with neighbors depend on place (neighborhood). The interactions within a soccer team depends on a combination of people and content (team members playing football) and a surfing community depends primarily on place and content (water and surfing). Interactions that depend on a combination of people and place include locations associated with social status and exclusivity of some kind, including private clubs but also areas like Beverly Hills in Los Angeles and Manhattan, or for that matter Brooklyn, in New York City. When a place manages to anchor content-specific interactions unbundled from the people interacting, it can form a scarce resource which enables positive reinforcement that attracts more people and interactions over time. Think of places like Madison Avenue in new York City, but also Silicon Valley.

Figure 4 : Anchoring interactions in places



Comment: How interactions are related to places depend on how people-, content- and place specific they are. Interactions that are predominantly people- or content-specific will only relate to a place as long as the necessary people and content is available there.

4.2 Future research

The results in this thesis are consistent with the idea that interactions scale nonlinearly with density and with population size, with the addition that it is not only the number of interactions but also their structure that determines their impact on the flow of knowledge and ideas in cities. These findings do not so much displace current research as it adds new nuances or slightly alternative approaches to the study of cities and our understanding of urban life. This section contains a brief discussion on how the thesis could be leveraged in existing lines of research, but also how the results could be elaborated on in new studies.

To the research on agglomeration economies and density externalities, the thesis adds to the link between city-wide productivity gains related to size and within-city localized externalities. In terms of future research there are two questions that stick out: First, how are agglomeration externalities distributed across the city and how do they relate to each other? Second, how do different parts of the population benefit differently from these externalities? The first question can for instance be addressed by studying networks between places (e.g. Batty 2013) and how they relate to agglomeration externalities. The second questions says something about the nature and direction of informational or knowledge spillovers.

Urban scaling analysis is extended from a inter-city scale of comparison to a within-city scale. First, the within-city spatial scale opens up a venue of scientific inquiry aimed at the self-organization of other types of activities like entrepreneurship, innovation or crime. Just as agglomeration externalities appear to differ in their expression across spatial scales, so too may the self-organization of different parts of a city's social and economic life. Second, integrating inter-city urban scaling analysis with within-city scaling could contribute to a fuller picture of the underlying networks and interactions that shape cities around the world. Assuming that the structure of interactions changes both quantitatively and qualitatively with population size, it is also relevant to ask how interaction structures change in shrinking cities, as well as how differences between small and large cities can be addressed in terms of policy measures.

Another potential line of research is concerned with the notion of cycles of adaptation and information processing in complex adaptive systems of local interactions. As suggested in the thought experiment at the end of the previous chapter, a cyclical perspective opens up for a studying how structural changes affect interactions and how they collectively adapt. This ties into research on diffusion of ideas and information. Also building on the thought experiment, exploring how different types of interactions become situated in places, a line of inquiry that could draw on insights from place-making and urban amenities research.

Furthermore, an aggregated view on information processing brings up the question of how different forms of knowledge differ in the way it is processed through interactions. More to the point, how does the level of knowledge complexity relate to how it is is is processed and spread in complex networks. This relates to what Hidalgo (2015) writes about the individual- and firm-level limits to knowledge management, or West's (2017) comparison between how cities handle information vis-a-vis companies. Studying the turnover of information and trends in cities may also provide valuable insights about cities of different sizes as environments for entrepreneurship and market places, for instance related to the so called sharing economy.

The thesis as a whole touches upon the integration of complexity science and evolutionary economic geography. Continuing this integration is a promising venue for future research, which may contribute to further elaboration of the idea of variation in evolutionary processes in local and regional economies.

4.3 Policy implications

Complex adaptive systems, the idea that the system-wide behavior is more than the linear sum of its parts, has several implications for policy-making, most importantly by changing the conditions on which policy-making is based.

The fact that a social and economic system like a city can transition into a more stable and ordered state "on its own", i.e. self-organize, has two important implications. First, it indicates that policy is not implemented in a passive environment and, consequently, that cities *adapt* to policy initiatives rather than just being unidirectionally *shaped* by them. This is consistent with the observation by West (2017) that cities, despite their diversity and differences in planning and regulation, exhibit a considerable degree of similar and predictable characteristics across the globe. Second, the presence of self-organizing principles suggests that the success of policy initiatives may be conditioned by the behavior and adaptability of the system. The internal organization of interactions matters whether the activity in question is considered positive or negative. If the aim of the policy for example is to target crime within a city, then it may help to better understand its self-organized amplification. In contrast, if a policy is designed to promote startup entrepreneurship and related activities, it helps to relate to how these activities self-organize in order to boost their amplification through positive reinforcement. These implications do not, however, add up to a straight-forward defense of market-driven policy.

A fundamental question and line of conflict in policy-making is the trade-off between state and market. Colander and Kupers (2014) distinguish between two extreme approaches in current policy-making, "state control" in which government makes the market operate more efficiently by correcting its failures and "market fundamentalism" that aims to keep the state out of the economy. The problem with this division, according to Colander and Kupers, is that both sides assume that the state and the market are independent from each other. In the state control model, the state is an external actor that picks policy solutions to correct the market, while in the market fundamentalist model, markets are part of an evolutionary process from which the state is excluded. In both of these narratives, it is at least theoretically possible to identify a correct optimal policy that applies to to all economies sharing similar traits at a given point in time. This picture blurs if we take into consideration not only the evolution of the market, but also the history of previous policies and reactions from the market, i.e. if state and market are considered to co-evolve with each other. If this is the case, then places with similar economic characteristics at one point in time are not interchangeable. In other words, it is not a question of market *or* state, but of market *and* state in coevolution (Colander and Kupers 2014; Beinhocker 2006). This approach echoes Hayek's (2012) conceptual model of co-existing grown and made order.

What should a complexity-oriented policy frame look like? Colander and Kupers argue that it must shift the attention from formulating policy that will lead to a specific outcome, towards formulating policy that creates "a viable social ecostructure in which individuals, or collections of individuals, solve problems from the bottom up, without the use of a central coordinator". Along a similar vein, Beinhocker (2006, p. 419) suggests that policy based on complexity economics should relate to people as "conditional cooperators and altruistic punishers", i.e. as part of a *tit for tat* culture (Axelrod 2007). What this means is that it is not only the outcome of policy that matters, but also whether this outcome was generated through individual actions or factors outside the individual's control. In other words, inequalities generated by individual choice are not the same as inequalities derived from structural factors.

When it comes to formulating actual policy, limitations like "without central coordination" and "factors outside the individual's control" will be subject to interpretation, but leaving the specifics of the two approaches aside they have two things in common: First, they advocate a shift in the balance between centralized and decentralized organization, which can be interpreted as a recognition of the need to take self-organizing principles into consideration when formulating and implementing policy. Second, and perhaps most importantly, both approaches underscore the need for more adaptability or responsiveness in policy, in response to the complex adaptability of the system it is implemented into. Policy is not considered a static construction, but a instrument that needs to adapt in co-evolution with the system it operates on in order to maintain its purpose.

How does this complexity frame translate to urban planning and policy-making? Batty (2013, p. 302) describes how planning has moved from treating the city as an artefact, based on the assumption that "cities in general were rather passive environments where plans could be defined quite independently from their functioning and their populations", to treating cities as processes. He states (ibid, p. 365) that "[a] view of planning that can easily accommodate changing value systems, the complexity of pluralism, and the notion of fallibility now seems more appropriate". Rose (2016) similarly describes the challenges that cities face as planning under VUCA – *Volatility*, *Uncertainty*, *Complexity* and *Ambiguity*. Drawing on systems thinker Donella Meadows, Rose argues that policy must relate to *leverage points* that can either stop positive reinforcement of a specific activity or promote it. Identifying and learning about such leverage points is, he argues, one of the biggest challenges for the future of urban planning and policy.

Against this backdrop, there are three general implications for urban policy that can be inferred from this thesis. First, that policy may benefit from relating to (either by amplifying or dampen) self-organizational principles. The findings in papers 2 and 3 imply that there are patterns of unevenness to urban economies, illustrated in paper 2 by within-city scaling of productivity gains with neighborhood-level employment density. The results also suggest that some of the observed scaling pattern may be related not only to density but also to specific places, and in addition that the results affect different parts of the aggregated wage distribution differently. Based on this, and the conceptual model presented in paper 1, it may for instance be argued that policy directed towards the spatial distribution of activities or people must take into consideration the element of self-organization that these patterns exhibit. This resonates with Rose's emphasis on leverage points, applied to spatial distribution. Taking into account that cities may be treated more as processes than artefacts, it is relevant to pose the question of whether or not social policy is better aimed at people (social mobility) and places (accessibility, crime) than towards spatial distribution (social housing)?

The second policy implication is that there may be a need for policy tools that mirror the view of the city as a process, but also a complex *adaptive* system of interactions. If policies have a fixed goal and the system they are implemented into is adaptive, then it can be argued that the policies themselves must be subject to change over time in some manner, i.e. the policies need to be adaptable. The conceptual model developed in paper one and fitted to empirical evidence of agglomeration externalities suggest that interactions self-organize, but also that this organization changes over time as the city grows or as new information causes interaction components to form, dissolve or shift their focus. This cyclical perspective is arguably mirrored by countless examples of policies with the aim of amplifying interactions, networking, knowledge transfer and entrepreneurship within a specific timely subject area. Equally evident is the shift in subject focus over time. This implies that the more subject-specific a policy program aimed at promoting information- and knowledge-intensive interactions is, the more time-sensitive it may become both in relation to the global development of knowledge and innovation and with respect to the organization of local interactions within the city. This corresponds to a temporal interpretation of Rose's leverage points. Drawing on this, policies aimed at promoting clustering of interactions or government-organized clusters should arguably either broaden their scope to accommodate cycles of subject focus, or be formulated as cyclical processes themselves rather than time-invariant artefacts. For example, Katz and Bradley (2013) provide a potential approach to generalized "innovation districts".

The third and final policy implication follows from the adoption of a complexity-oriented policy framework together with the former two implications. If policies become more process-oriented and shift from central control to decentralized organization, this may arguably challenge the level of granularity (i.e. the scope or detail of regulation and the narrowness of the stakeholder group targeted) that regulation can take on and still remain both effective and adaptable. Put differently, the scope of what can actually be regulated and at what level of detail of that regulation shrinks compared to more static and centralized policy models. This implies a need for "coarse-grained" policy measures to match the coarse-grained theories in scientific work that West (2017) and other complexity scientists advocate.

Together these implications may for example provide a crude motivation for formulating "learning" policy programs driven by local experimentation, i.e. a operationalization of co-evolution. This type of approach may fit well within the framework of smart city policies, but is not guaranteed by it (Campbell 2013).

Cities are becoming increasingly more complex with size because of the interconnectedness of interactions between people (Batty 2013, Colander and Kupers 2014). Along this vein they are also becoming more complex with digitization as people become more interconnected not only with each other but also with machines (and machines with other machines in the growing internet of things). Therefore, we have reason to believe that a urban policy toolbox that can maneuver complex adaptive systems is only going to become more important in the future as more people move into both small and large cities.

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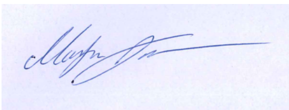
To whom it may concern,

Martin Andersson, Johan P. Larsson and Joakim Wernberg hereby certify that the articles “The microgeographies of diversity and specialization” and “Social capital and the economics of cities” are based on equal contributions from each author.



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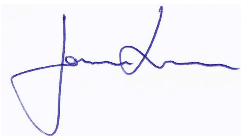

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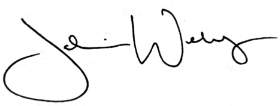

Joakim Wernberg