Chapter 5
Complexity Theories of Cities Have Come of Age: Achievements, Criticism, and Potentials

Complexity theories of cities (CTC) have come of age. What some two and a half decades ago was a narrow stream of studies – written mainly by physicists applying theories from physics – has now become not a flood but an established interdisciplinary research domain engaging urban geographers, planners, urban designers, regional scientists, mathematicians, physicists and others. In addition to the constant flow of articles, we start to see attempts at integration in the form of spatial theme issues (*Environment and Planning A*, 2006) and of books (Pumain 2006; Benenson and Torrens 2004; Allen (1997), Portugali 2000, 2006; Batty 2005). In such attempts at integration it is just natural to find appraisals of what has been achieved by CTC in the last two decades and a half.

As the title of this chapter indicates, the aim below is to look back at what has been achieved in the domain of CTC in the last three decades; however, the aim is to do so with appreciation, but also with sober criticism, and then, to look forward at potentials that have yet to be realized. The discussion below thus develops in three steps: achievements (Sect. 5.1), criticism (Sect. 5.2), and potentials (Sect. 5.3).

5.1 Achievements

In the introduction to his *Cities and Complexity*, Batty (2005) notes that CTC have provided sound theoretical basis with mathematical formalism to the intuitive ideas suggested by Jean Jacobs (1961) (and Christopher Alexander too) more than 40 years ago. In a recent *Science* article he writes the following:

> *In the past 25 years, our understanding of cities has slowly begun to reflect Jacobs's message. Cities are no longer regarded as being disordered systems. Beneath the apparent chaos and diversity of physical form, there is strong order and a pattern that emerges from the myriad of decisions and processes required for a city to develop and expand physically. Cities are . . . par excellence complex systems: emergent, far from equilibrium, requiring enormous energies to maintain themselves, displaying patterns of inequality spawned through agglomeration and intense competition for space, and saturated flow systems that use capacity in what appear to be barely sustainable but paradoxically resilient networks.* (Batty 2008, pp 769–771).

J. Portugali, *Complexity, Cognition and the City*, Understanding Complex Systems,
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Similar things can be said of the relations between CTC and other "classics of urban studies". Allen's dissipative cities, as we have seen above (Chap. 4, Sect. 4.2.1), is in a way a reinterpretation and reformulation of Christaller's central place theory in terms of Progogine's dissipative structures; Sasaki and Box (2003) suggested "Agent-Based Verification of von Thünen's Location Theory"; Weidlich's synergetic cities (Chap. 4, Sect. 4.2.2), applies Haken's theory of synergetics to population distribution in cities; our own synergetic and FACS cities (Chap. 4, Sect. 4.4.2) suggest a reinterpretation to the "old" ecological and economic approaches to cultural segregation in cities in terms of synergetics and FACS theories; and just recently the close to 100-years-old rank size rule of Auerbach (1913) is being reinterpreted in terms of Barabasi's and Watts' "new science of networks" and its power law distribution (e.g., Batty 2005). Finally, it is interesting to note that what Batty said above about Jacobs, applies also to Christopher Alexander's messages of the 1960s and 1970s, namely, that the new science of networks reconfirms Alexander's (1965) view from the 1960s that 'a city is not a tree' but rather a complex semi-lattice network, and, that beneath the apparent chaos and diversity of physical form that typify cities, there is a highly ordered *pattern language* that exist in humans' heads and in the world (Alexander et al. 1977).

The first achievement of CTC is thus not so much in identifying new urban phenomena as in giving a single and sound theoretical basis to a variety of urban phenomena and properties that so far were perceived as independent of each other and thus interpreted by reference to different theoretical bases: The pattern of land use in cities that in the past has been interpreted in terms of Thünen's economic theory, the spatial segregation of ethnic, cultural and socio-economic social groups in the city that in the past has been interpreted in ecological terms, the size distribution of cities in a region, the economic and geographical spatio-hierarchical pattern of central places in cities, metropolitan regions and countries, the structure of road networks of cities as well as the structure of communication between cities, the perception of cities and more urban phenomena (see Chap. 2, above), all have today a single theoretical basis; all have already been interpreted as complex networks emerging out of local interactions between urban agents that give rise to the global structure of cities (Fig. 5.1).

The second achievement of CTC is that it has added new insights to our understanding of cities – new insights that reflect the very basic properties of complexity. A few (and by no means inclusive) examples will illustrate this point:

First, complex systems, cities included, are typified by the property of nonlinearity. In the case of cities this implies that the local action and/or behavior of a single and "small" urban agent (say, a single person) might affect the city much stronger than the action of a big and strong agent such as the city planning team. This (somewhat counter-intuitive) insight sheds new light on the role and importance of the human individual in shaping the urban landscape and its dynamics. A case in point is the story of Tel Aviv balconies as presented below in Chap. 15, Sect. 15.1.3.

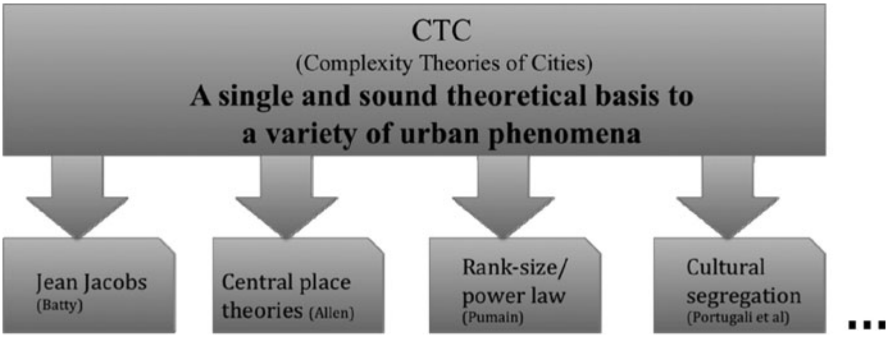

Fig. 5.1 CTC provide a single and sound theoretical basis to a variety of urban phenomena and properties that so far were perceived as independent of each other and were thus interpreted by reference to different theories

Second, complex systems, cities included, are typified by the phenomenon of *emergence*. In the case of cities it means that the local interactions between urban agents often give rise to properties that exist only at the global scale of a city. For example, that a high level of cultural/ethnic segregation in a city, does not imply highly segregative behavior on the part of individual urban agents. As illustrated in the past (Portugali 2000) and below (Chap. 17), a very small proportion of segregative urban agents might give rise to a highly segregative city. The lesson is that we have to be aware of the differences between the individual and the collectivity. (Note that this phenomenon can be interpreted also by reference to the property of nonlinearity).

Third, the property of emergence further implies that the city, by means of its very dynamics, can give rise to new urban entities and identities – for example, to a new cultural group. As illustrated in the past (Portugali 2000) and below (Chap. 17), several of the cultural groups that characterize the multicultural cities of our time, were created in this way. This, in its turn, implies that we have to see the city not only as a representation of larger socio-economic or cultural forces, but as a socio-cultural force in itself.

Fourth, some cities are often described as symbols of order while others as symbols of chaos. As noted above, CTC teach us that "beneath the apparent chaos and diversity . . . there is strong order and a pattern . . .". Furthermore, from the notion of *edge of chaos* (Kauffman 1993; Langton 1990) follows that chaos and order do not necessarily contradict one another. With respect to cities this implies that, firstly, the tension between chaos and order often keeps cities on "the edge of chaos" – a situation that enables cities to be adaptive complex system and withstand environmental changes (Batty 2005, pp 479–482). Secondly, in some cases pockets of "captive" urban chaos might be necessary in order to maintain the stability of the rest of the city (Chap. 4, Sect. 4.3.1.3). Thirdly, chaos might be the precondition for new order to emerge. For example, pockets of captive urban chaos are areas of high potential for change (ibid).

5.2 Criticism

In early 2008 I was invited by sLIM (http://www.slim.nu/en/lg11introen.php) to give a talk on "The theory of self-organization and its potential for addressing the 21st century city both in the developing and developed world". The motivation for this meeting was the observation that the 21st century is marked by a strong sensation of change the signs of which are abundant: Globalization, civil society, privatization, the decline of the national welfare-state and of course cities; cities capture the core of this change: For the first time in human history more than 50% of world population live in cities, several cities around the world turned into mega-cities with population of over 20 million, the economy and sphere of influence of many world or global cities extend beyond the boundaries of their nation state and yet parallel to and within this trend we see a countertrend toward localization or "glocalization". The above sensation and situation shows itself also in the increasing popularity and dominance of theories and perceptions of reality that emphasize change and instability; in the shifts from modernism to postmodernism, from structuralism to poststructuralism, from constructivism to deconstuctivism, from systems in equilibrium to systems in far from equilibrium, from closed to open systems, from entropy to self-organization and complexity with notions such as chaos, edge of chaos, fractal structure, nonlinearity and the rest (Portugali 2005a).

It is therefore not surprising that some of the basic aspects of 21st century society and cities are often described in terms taken from the language of complexity theories and CTC: The most prominent example is Castells' (1996) *The Rise of the Network Society* and his notions of *space of flow* and *information city*. A more recent example is Healey's (2007) book *Urban Complexity and Spatial Strategy*. It is important to note that both Castells and Healey are using the notion 'complexity' literally without the theoretical formalism and meaning added to it by complexity theory. On the other hand, Thrift (1999), in a paper on "The place of complexity", refers to complexity theory itself.

The idea of the students who organized the sLIM seminar was that CTC must have a lot to say about the 21st century city. Preparing the talk I realized that while this is indeed the case, so far CTC have said very little about the 21st century city and its specific properties. Most researchers in the domain of CTC preferred and still prefer to focus on rather traditional, conservative and somewhat anachronistic urban issues: central place theory, land use, rank-size distributions of cities, national systems of cities and the like – issues that were dominant in the 1950s and 1960s.

As we've seen above in some detail (Chap. 3) in the early 1970s the study of cities underwent a kind of paradigm shift when several students of the quantitative-positivist approach to cities – David Harvey being the most predominant of them – started to criticize their own camp on the ground that the arsenal of scientific theories and methods developed by quantitative urbanists and location theorists is "incapable of saying anything of depth and profundity.." (Harvey 1973, p 129) about the real problem of cities in the 1960s and 1970s. We've have further seen above that the result was a split between the two cultures of urban research and that the hermeneutic-critical approach dominated the field for more than two decades.

Can we or should we draw a parallel between the tension between the two cultures of cities – the scientific and the humanistic – some 40 years ago and today? Is there a ground to say that CTC are "incapable of saying anything of depth and profundity.." about the burning urban issues of the 21st century city – about processes of globalization and glocalization, about the emergence of megacities of over 20 million people, of urban planning and governance in a society with emerging civil society? I don't think so; not only because CTC have a potential (that has yet to be realized) to add new insight to our understanding of 21st century urbanism, but also because it has a potential to go beyond the two cultures of cities and in fact to unite them (Portugali 2006a and below Chap. 11). On the other hand, I do think that there is a danger that if CTC go in their current direction they will soon become a new version of the old quantitative approach and as such subject to the same criticism leveled at it in the early 1970s.

5.2.1 What Went Wrong?

What is the current trend of CTC and why it might lead to irrelevant urban studies? The answer in short is that the current trend is to see CTC as a new generation of quantitative urban simulation models (USM) capable of describing, simulating and predicting urban scenarios in an efficient and accurate way – much better than the old generation of quantitative methods of the 1950s, 1960s, and 1970s. Implicit in this current trend is the view that what gives the new generation of USM an edge over the old generation is, firstly, the mathematical formalism and simulation methodologies developed by the various complexity theories, in particular cellular automata (CA), agent base (AB), and more recently network models (Chap. 4, above); secondly, the new computation technologies that enable to run the new and more sophisticated USM and to crunch huge amounts of data.

There is nothing wrong of course in sophisticated simulation models crunching huge quantities of data by means of fast computers. What's wrong is, firstly, that simulation models originally designed as media by which to study phenomena of complexity and self-organization become the message itself. Secondly, that CTC tend to overlook the fact that complexity theories form a new science that is critical of the first culture of cities. Thirdly, and as a consequence of the above, that most studies in the domain of CTC are silent about the qualitative message of complexity theories to cities. Fourthly, that students of CTC have indiscriminately applied to cities theories and models originally developed to deal with natural phenomena, ignoring the implications of the fact that cities are not natural phenomena but rather artifacts. Let me elaborate.

5.2.2 The Medium is the Message

"The Medium is the Message" is a notion coined by McLuhan (1964), suggesting that the medium by which a message is being conveyed participates in forming its content; and, that in some cases the medium becomes the message itself. A book versus a television are often cited as two media that affect differently the content of a given message. To the latter I would add mathematical models and USM, too. The situation by which USM have become the message shows up in several phenomena and trends. Firstly, CA and AB USM, as noted above, have become the most popular approach to simulate the dynamics of cities. Their popularity stems from the fact that they are intuitively related to the dynamics of cities, simple to use, and easy to run with empirical data. And indeed the insight they added and still add to our understanding of cities is rather important. On the other hand, however, their intensive use is not without a price: The medium has too often become the message; too often complexity theories of cities and cities themselves are seen through the "eyes" of CA/AB models – as theories of cognitively simple interacting agents that in a bottom-up process give rise to cities and systems of cities that are stable and robust. The problem is that as we'll see in some detail below (Part II), urban agents are cognitively complex and cities are not robust – not if we study their *longue durée*, that is, their long-term evolution and dynamics.

Secondly, in their search for statistical data to feed their models, practitioners of urban simulation models tend to overlook the nonquantifiable urban phenomena. This is so with respect to "classical" qualitative urban phenomena such as those of the 21st century cities mentioned above and this is so also with respect to classical phenomena of complexity theory. A case in point is the phenomenon of chaos that as we've seen above (Chap. 4 Sect. 4.3.1) is not on the agenda of CTC. The reason to my mind is that chaos is hard to identify in cities by means of published statistical data and as a consequence, with few exceptions (ibid), there are no applications of chaos theory to cities.

Thirdly, the medium of CA/AB has too often become the message in yet another respect: many students in the domain of CTC and USM tend to employ CA/AB USM as sophisticated predicting devices, overlooking the fact that complexity theories imply that complex systems are essentially unpredictable – the elementary properties of the theory, such as nonlinearity, chaos, emergent properties and the like imply unpredictability. By so doing these practitioners of complexity theory run into a paradox: they claim that cities are complex systems but they treat cities as if they were simple systems.

5.2.3 Implicit Criticism

Proponents of CTC are by and large sympathetic with the first science of cities and implicitly or explicitly regard themselves as belonging to the first culture of cities as the new, more sophisticated, science of cities. What they often fail to see, however, is that CTC have two significant interfaces with the second culture of cities, namely, with SMH and postmodern cities. Firstly, similarly to social theory oriented urbanism, CTC is critical of classical urbanism and planning. Secondly, and related to the above, CTC perceive the urban process in a way similar to social theory oriented urban studies. The aim of this section is to elaborate on the first interface.

CTC never explicitly criticized classical urbanism and yet the criticism is there, implicit in the very logic of CTC: Classical theories of cities assume that cities are essentially closed systems and as such tend toward a state of equilibrium (e.g., the classical location theories of Thünen, Weber, Christaller and Lösch and their followers) and maximum entropy (e.g., Allen Wilson's family of entropy maximization models – Wilson 1970). CTC per contra assume that cities are essentially open systems and as such are in a permanent state of "far from equilibrium condition" and "on the edge of chaos. Furthermore, classical urbanism and planning theory pre-supposes that cities are essentially predictable and as such controllable and planable (e.g., the rational comprehensive planning approach); CTC as we've just seen (and will further see below) imply the exact opposite.

Needless to stress that the above criticism has yet to be fully elaborated and spelled out; its essence, however, is apparent. It is also apparent that by overlooking this criticism proponents of CTC often tend to treat "their" complex, self-organizing cities as if they were classical systems – in the case of PSS (Planning Support Systems), for instance (see Chap. 12).

As we've seen above, social theory oriented urban studies are critical of the first culture and science of cities for applying to cities positivism – the quantitative scientific method that was originally developed for the study of matter and mechanistic phenomena. They claim that the human domain is fundamentally different from the domain of nature and as a consequence the application of the scientific approach to the study of cities and the practice of planning leads to reductionism; in the human domain, they claim, the "soft" hermeneutic approaches are therefore more appropriate. Marxists further claim that positivism is not just an inappropriate approach mistakenly applied to the human domain but an ideological false consciousness that obscures people's view from their real state of existence in an unjust capitalist social structure.

CTC agree with social theory oriented urban studies that the human-urban domain is different and that therefore applying the classical approaches to the human domain of cities leads to reductionism and misconception of the urban process, and, that the specific structure of society and the city must be taken into consideration when studying cities; but they agree on the above for a different reason: the complexity of the system. Classical urban theorists and planners have treated the city as simple and classical and yet it is complex and nonclassical. In fact, as implied by Batty (2008), the message was on the wall already in the 1960s – in what has been termed above (Chap. 3, Sects. 3.4, 3.5; Chap. 4, Sect. 4.5) as *the third culture, namely*, in the writing of Jean Jacobs (1961) and Christopher Alexander (1965) who have perceived cities as complex systems several years before formal complexity theory came to the fore. But classical urbanists failed or rather were not able to respond to these new ideas because they were part of, and enslaved by, the first culture of cities.

5.2.4 The Qualitative Message of Complexity Theory to Cities

Most CTC studies ignore the new insight that complexity theories can add to our understanding of cities in general and to the cities of the 21st century in particular. Batty's discussion about the general message of CTC as described above and few other studies about this issue (Portugali 2000, 2006a) are exceptions that prove the rule. One reason for that has already been suggested above: The qualitative urban phenomena do not lend themselves to quantitative-statistical analysis and thus are of little interest to mainstream CTC: The growth of cities beyond the nation state, the role of civil society in their dynamics, the implications of complexity and self-organization to planning and design, like other burning questions of 21st century cities, are all "qualitative", with no "hard" data and as such not in mainstream discourse of complexity theories of cities. It must be emphasized that some qualitative urban phenomena can and have been modeled and simulated by means of CTC USM. For example, our FACS models have been employed to study the process by which the urban dynamics entails the emergence of new socio-cultural groups in the city (Portugali 2000, Chap. 8, and see Chap. 17 below). However, since there is no simple way to back such models by "hard" quantitative data they are treated as too theoretical or "pedagogic" (Batty 2005) and as such less attractive.

One might justly argue that every research domain has boundaries and that the above qualitative issues of complex agents and of 21st century cities fall beyond the boundaries and scope of CTC. My view is that this is not the case. One reason for this view is that so far complexity theories were applied to cities only partially, that is, only selected parts of the processes that make a system complex were applied to the domain of cities. A second reason is that CTC have not as yet crossed the boundary of simple, mechanistic applications.

5.2.5 Partial Application

In the previous chapter it has been suggested to distinguish between comprehensive or long-term complexity theories vs. short-term complexity theories, while on the other, between complexity *theories* of cities and complexity *models* of cities. From the perspective of these distinctions one can observe, firstly, that while the founding theories, namely Prigogine's dissipative structures and even more so Haken's synergetics, were comprehensive theories, putting full emphasis on all three aspects and long-term evolution of complex systems, subsequent theories became more specific. Secondly, that CA, AB and network urban simulation models that currently dominate the field focus mainly on the process of emergence, that is, on the dynamics by which local interactions give rise to a global structure.

There is nothing wrong, of course, with the above trend as long as the various approaches complement each other – as long as more theoretical viewpoints shed light on the multiple aspects of complex systems. It starts to be problematic, however, when in order to make their point, the new theories, models and points of views put shade on, or dismiss as not "quantitative" or "scientific" or up to date, previous ones. This is exactly what happened in the domain of CTC. It started with comprehensive complexity theories of cities and urbanization that theorized about both the short and the *longue durée* of cities and urban processes. However, as more and more researchers joined the club, the comprehensive view of cities and urbanism was put aside and the theoretical focus moved to the short-term urban phenomena. One result was that CTC became less and less relevant to the general study of the long-term qualitative aspects of cities and urbanism – exactly the kind of issues that today typify 21st century cities and urbanism and today stand at the center of interest of the general discourse about cities. Furthermore, as we've seen above, while the long-term CTC tended to employ USM as a medium by which to explore the various aspects, in the short-term CTC and specifically in complexity models of cities, the medium of USM has become the message and the search for data to feed the models led many to ignore urban phenomena on which there is no easily accessible quantitative data.

5.2.6 Adaptive vs. Nonadaptive Application

Complexity theories were originally developed in the sciences and by reference to natural phenomena, thus for example, the Bénard experiment was employed by Prigogine in developing his dissipative structure, Haken has developed his theory of synergetics by reference to Bénard and the phenomenon of the LASER beam, and Bak's theory of self-organized criticality was inspired by the sandpile experiment. An exception is Mandelbrot who started to developed his theory of fractals by reference to the economy (Barcellos 1984) and to *The (Mis)Behavior of Markets* (Mandelbrot and Hudson 2004). However, his theory became fully accepted and appreciated when he demonstrated *The Fractal Geometry of Nature* (Mandelbrot 1982) and when the theory was applied to processes that give rise to snow flakes (Koch's algorithm) or to plants (Lindenmayer's algorithm). All these theories were applied to cities as we've seen in some detail above – applied in a *mechanistic* but not *adaptive* way.

Complex systems are often described as *complex adaptive systems*, that is, systems capable of adapting their structure and behavior to the environment into which they enter or are being introduced (Gell-Man 1994; Holland 1992). A human being is a typical adaptive system. Adaptability is an important property of complex systems resulting from the fact that such systems are open and capable of self-organization. Nonadaptive systems, per contra, maintain their structure irrespective of the environment. Nonadaptability is a property of closed, simple and mechanistic systems.

In *The Quark and the Jaguar* Nobel Laurent in physics Gell-Mann (1994, p 17) characterizes a complex adaptive system as follows:

> *... a complex adaptive system acquires information about its environment and its own interaction with that environment, identifying regularities in that information, condensing these regularities into a kind of 'schema' or model, and acting in the real world on the basic of that schema. In each case there are various competing schemata, and the results of the actions in the real world feed back to influence the competition among those schemata.*

It is interesting to mention in this connection, firstly, the similarity to Haken's *synergetics* as described above; in particular the similarity between Gell-Mann's *schema* and Haken's *order parameter* and also the emphasis of both on the competition between schemata/order parameters and on feedback with the real world. Secondly, the similarity to Prigogine with Stenger's (1997, p 62) who compared the closed system 'crystal' to the open system 'town': "A crystal", they write, "can be maintained in a vacuum, but if we isolate the town, it would die ...". The property of *Openness* that typifies complex systems is thus a precondition to their *adaptive* capability.

In light of the above, I suggest a distinction between *adaptive to nonadaptive applications*. By *adaptive applications* I refer to situations by which a theory or notion is being transferred from one domain to the other by adapting its structure to the specific properties of the new domain. By *nonadaptive applications* I refer to situations by which a theory or notion is being transferred from one domain to the other by maintaining its structure irrespective of the specific properties of the new domain.

With few exceptions, most complexity theories were applied to cities in a nonadaptive manner. One part of these applications was made by physicists whose main interest was not cities but the models they applied. This is evident from the fact that many such papers are published in journals such as *Physica A*. For these physicists as well as for the editors of the above journals, cities are nothing but another source of data by which one can feed and test the models. The important finding of such studies is that the size distribution of several systems of cities obeys the *power law*, that several cities, metropolitan regions, rail and road networks are *fractals*, that many cities and their road networks are *small world* and so on. Another part of the applications was made by students of cities and urbanism attracted by the opportunity to develop a science of cities that is based on the strong theoretical and methodological foundations of complexity theories. The fruits of the various applications are that today we have the domain of CTC and USM with significant achievements as described above.

And yet, cities are not natural entities such as liquids, light beams, snow flakes, sand-piles or trees and their parts are not atoms or molecules, or sand grains. Cities are *artifacts*, that is, artificial systems – *facts of art* and human culture – and their parts are human beings that unlike sand grains can think, learn, plan, forget, change their mind, ... and their actions and behavior are products of intentions, plans, social and cultural norms, political pressure and the like. These properties enable humans to adapt to their environment and these properties make each human being a complex, self-organizing adaptive system. The fact that CTC and complexity models of cities tend to overlook this uniqueness of cities entails a twofold problem: First, there is a limit to what CTC in their present nonadaptive form can say about cities – they can say very little on the really interesting and qualitative problems of cities in the 21st century. Second, CTC have no new feedback to complexity theories, no new insight or new contribution to the general domain of complexity theory.

5.2.7 The Limits of Nonadaptive CTC

CTC show that cities and transportation routes are fractals, that their size distribution obeys the power law, that bottom-up local interactions between simple agents can give rise to complex global patterns of land-use and ethnic segregation and so on. But what does it mean that a city is fractal? That a system of cities is fractal? Why are they fractals and are typified by a power law distribution? What do we learn about cities from the fact that they can be modeled and simulated in a way analogical to sand-grains or trees? Some forty years ago Wilson (1970) has demonstrated that entropy maximization spatial interaction models can mathematically describe a whole set of urban phenomena ranging from transportation, to retail, housing and more. Entropy, as is well known, is a property of closed and simple systems and as such the exact opposite of complex self-organizing systems. Nowadays, CTC demonstrate that its urban simulation models can explain the same set of urban phenomena as properties of open and complex systems. In what family of models should we believe – in the models that treat cities as closed systems, or in models that treat cities as open systems? I make this point not in order to discredit complexity models of cities, but to emphasize that a best fit between model and data is not enough. The fact that a given model can successfully generate a tree and a city doesn't mean that a city is a tree – it is not.

As discussed above (Chap. 4), in 1965, Alexander published a paper that has since become famous: "A city is not a tree". In this study, Alexander makes a distinction between two ways of thinking about cities: one is in terms of a hierarchy or a tree, and the other in terms of a semi-lattice (above, Fig. 4.33). The two cities differ from each other in their structure – a tree vs. a semi-lattice, and in the processes that created them and that take place in them.

In this article Alexander demonstrates that despite the similarity between the hierarchical structure of a tree and that of a city (or system of cities), a city is a much more complex network than a tree – it has a semi-lattice structure. In the "tree city" each subsystem in the city is independent from all other subsystems of its level, and it can thus interact with them only via a higher order subsystem. In the semi-lattice city there are overlaps between subsystems of the same order, so that interaction can occur vertically, horizontally and in oblique. As noted by Alexander, it is not only the overlap which makes the difference, but

> *more important is the fact that the semi-lattice is potentially a much more complex and subtle structure than the tree..: a tree based on 20 elements can contain at most 19 further subsets of the 20, while a semi-lattice based on the same 20 elements can contain more than 1,000,000 different subsets* (Alexander 1965, p 382).

Students of CTC like to quote this paper because it implies that cities are very complex networks. Alexander wrote about these differences as an urban designer with the aim to negate "natural" to mechanistic cities:

I want to call those cities which have arisen more or less spontaneously over many, many years natural cities. And I shall call those cities and parts of cities which have been deliberately created by designers and planners artificial cities. Siena, Liverpool, Kyoto, Manhattan are examples of natural cities. Levittown, Chandigarh and the British New Towns are examples of artificial cities.

This terminology is to my mind misleading for the simple reason that unlike the *tree*, which is by definition a genuine natural entity, Siena, Liverpool, Kyoto, Manhattan as well as Levittown, Chandigarh and the British New Towns are all *artifacts*. The more significant question is therefore 'what makes artifacts such as Siena or Kyoto more complex (with a semi-lattice network) than the natural entity tree and cities like the British New Towns? The answer is implicit in Alexander's paper:

For example, in Berkeley at the corner of Hearst and Euclid, there is a drugstore, and outside the drugstore a traffic light. In the entrance to the drugstore there is a newsrack where the day's papers are displayed. When the light is red, people who are waiting to cross the street stand idly by the light; and since they have nothing to do, they look at the papers displayed on the newsrack which they can see from where they stand. Some of them just read the headlines, others actually buy a paper while they wait.

This effect makes the newsrack and the traffic light interactive; the newsrack, the newspapers on it, the money going from people's pockets to the dime slot, the people who stop at the light and read papers, the traffic light, the electric impulses which make the lights change, and the sidewalk which the people stand on form a system – they all work together.

They all work together because of the *human agents* that are involved in the dynamics that unlike the traffic lights, the newsrack and the headlines, can see and read from a distance, change their trajectory and buy a newspaper, and by means of these cognitive capacities the people, the newspapers, the traffic lights and the other spatially fixed objects form a system – "a unit in the city" as Alexander calls it.

A tree is a typical example of a complex system and a typical example of a fractal structure that can and has been generated by a variety of algorithms including CA. So far CTC has demonstrated that a city is a tree. To go beyond that, CTC have to look not only at the similarities between natural and artificial entities but also at their differences. The same applies to the relations between CTC and complexity theories at large: as long as CTC will treat cities as trees, as long as they will apply the various complexity theories mechanistically in a nonadaptive way, they will not be able to add and contribute to the general theories of complexity; in order to contribute to this general body, CTC will have to look not only at the similarities between natural and artificial entities but also at their differences (see Wilson 2006 for the contribution to complexity theory). Two such differences that concern the specific nature of urban agents and cities as artifacts are discussed below in Chap. 6, Sect. 6.5.3.2.

5.2.8 Simple vs Complex Agents

Studies on cities show that many of the properties of urban objects (e.g., land value, cultural image, etc.) are determined by their relations to their nearest neighbors. CA is a model in which the properties of every cell are determined in a similar way: by the cell's relations to its nearest neighbors. This similarity makes CA a rather attractive model to simulate cities. Their disadvantage is that in cities we have, in addition to relations between objects/cells, relations between the many urban agents. CA cannot simulate these relations, at least not explicitly and it is here where AB models come in – they add to the dynamics of urban objects the action of, and interaction between, the many urban agents. As the name AB indicates, the agent is the most important entity of this kind of models. But what is an agent in general and in the context of cities in particular?

In *Cities and Complexity* Batty (2005) addresses this issue. Surveying the literature on the history and meaning of the notion *agent* he defines agents as:

> *. . . objects that do not have fixed location but act and interact with one another as well as the environment in which they exist, according to some purpose. In this sense agents are usually considered as acting autonomously. . . . Autonomous agents thus cover a wide variety of behaving objects from humans and other animals or plants to mobile robots . . .* (Batty ibid, pp 209–210).

He then follows Franklin and Graesser (1997) and classifies agents' action and sensing capabilities as ranging between "passive" agents that can only react to what they encounter in the environment, to "cognitive" agents that in addition to reaction also act according to some protocols and goals. Batty then introduces a set of urban simulation models. Some of these urban models are reactive, while others are "cognitive". From Batty's survey it is not clear whether or not urban agents are reactive or cognitive nor whether urban agents are similar to or different from agents in other domains. Apparently this is so since his models are generative. In fact there is no discussion in the literature of CTC about the nature and meaning of urban agents.

The absence of such a discussion is more severe in face of the fact discussed above that since the mid-1950s there is a science of cognition that studies the nature of agents and since the early 1960s there is a branch of cognitive science that specialized in spatial cognition and behavior of agents including urban agents, that is, how human agents perceive and cognize space, how they navigate and behave in space, or take location decisions (Kitchin and Blades 2002; Portugali 1996a, 2004, 2005). Apart from a few exceptions, CTC ignore this body of knowledge.

5.3 Potentials

The potential contribution of complexity theories of cities that has yet to be realized is implied by the criticism discussed above. Let me emphasize the main points. First, as noted above, so far CTC have exhausted mainly the short-term theories.

The potential that has yet to be realized here is thus to further elaborate on the long-term CTC and to create a better balance between the short-term and long-term aspects of cities as complex self-organizing systems. This issue is discussed in Sect. 11.3.1 entitled "CTC: The deeper messages".

The second potential follows from the fact that complexity theories came and still come with quantitative and qualitative messages and from the observation that so far CTC have applied mainly the quantitative message. The potential that has yet to be realized is to develop a better balance between the qualitative and quantitative messages of complexity theories and their application to the study of cities. As emphasized in the past (Portugali 2000) and as will be further emphasized below, CTC have the potential to bridge between the two cultures of cities, that is, the "quantitative" science of cities and the "qualitative" social theory oriented study of cities.

The third potential concerns building links between social theory oriented urban studies and CTC. This potential is a corollary from the second one. As noted above and as will be further elaborated below, some of the qualitative insights already added by the CTC to our understanding of cities are similar to ideas that have developed independently in the context of the general study of cities, for example, the role of bottom-up urban processes. In social theory oriented urbanism the bottom-up approaches reflect a political and/or ideological stand; in CTC it is a property of cities as complex self-organizing systems. As will be shown below, there are many interesting links between social theory derived, and complexity theories derived, interpretations of cities and urbanism.

The fourth potential is to develop CTC oriented theories of urban planning and design. In the 1950s and 1960s mainstream-planning theory has developed as the applied branch of the first culture of cities. As we shall see below in Part III, the emergence of the second culture of cities had a strong impact on urban planning (and design) in the sense that since the early 1970s to date, planning theory is developing as an aspect of the second culture of cities, namely, of social theory oriented urban studies. This is one of the reasons to my mind for the almost absence of links between CTC and mainstream planning theory. A better link between CTC and social theory oriented urban studies will provide a good context to realize the potential of a CTC approach to urban planning and design. Chap. 15 below discusses the interrelations between CTC, social theory oriented urban theory and planning.

Finally, the fifth potential is to develop CTC as an adaptive application of the main body of complexity theories. As noted above so far most CTC are essentially nonadaptive applications indicating and emphasizing the similarity of cities as complex systems to complex material and organic natural systems. While important, this is not sufficient. The potential yet to be realized is to study also the differences between material and organic systems as complex systems, and cities as complex systems. Two such differences were mentioned above: Firstly, urban agents as the parts of the complex system 'city' are cognitively different from other animals as parts of organic systems and obviously from entities that form the parts of material complex systems. Secondly, cities are artifacts. The challenge is thus to develop a cognitive approach to CTC and to study cities as artifacts. Realizing this potential is the key for the realization of the four potentials discussed above and is also the task of the remainder of this book.

5.4 Concluding Notes

CTC is today at a crossroad or to use the language of complexity theories, at a bifurcation point. Two main attractors can be observed from this position: one, that CTC belong to the first culture of cities and should thus be seen as the second science of cities – more elaborated and sophisticated than the previous one that dominated the field in the 1950s and 1960s for the reasons noted above: it has better technology, stronger theoretical basis and more sofisticated urban simulation models. This first attractor is currently the dominant one, as we've seen, but it has several severe drawbacks that have been specified above.

The second attractor is that CTC will realize its full potential by building two bridges: one between CTC and social theory oriented urban studies. This bridge will link CTC to the main body of urban theory and, as a consequence, to the central issues of 21st century urbanism. The second bridge is between CTC and cognitive science or more specifically with environmental/geographical cognition – that branch of cognitive science that deals with human (and animals') cognition and behavior in large-scale extended environments which in the case of humans includes also cities and systems of cities. Based on these two bridges CTC will be able to develop its own identity within the overall field of complexity theories as a science of complex artificial environments and thus become the link between the two cultures of cities – a point of view I've started to elaborate in a paper entitled "Complexity theory as a link between space and place" (Portugali 2006) and will further be elaborated in the chapters below.