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Connecting the Fractal City

Living cities have intrinsically fractal properties, in common with all living systems. The pressure to accommodate both the automobile and increased population growth led twentieth-century urbanists to impose anti-fractal geometrical typologies. The fractal properties of the traditional city were erased, with disastrous consequences for the urban fabric. To undo this damage, it is necessary to understand several things in some detail: *(i)* what these fractal properties are; *(ii)* the intricate connectivity of the living urban fabric; *(iii)* methods of connecting and repairing urban space; *(iv)* an effective way to overlay pedestrian, automotive, and public transports; and *(v)* how to integrate physical connections with electronic connections. First of all, some basic misunderstandings about fractal structure have to be cleared up. I will then underline the nature and importance of hierarchical coherence. We can use the fractal criterion to test the geometry of cities as one condition for their success. Another independent criterion is connectivity, which has to be studied topologically. I will use lessons learned from the evolution of biological systems and the internet to discuss the distribution of sizes, inverse-power scaling laws, and 'small-world' networks. These concepts show us that extreme densities favored in contemporary urbanism – suburban sprawl on the one hand, and skyscrapers on the other – are pathological. The challenge for the contemporary city is how to superimpose competing connective networks in an optimal manner.

Introduction

This Chapter describes distinct types of cities as characterized by their connective geometry. The different types contain entirely different degrees of urban life. The life of a city is directly dependent upon its matrix of connections and substructure, because the geometry either encourages or discourages people's movements and interactions. Such an understanding is crucial for superimposing the electronic city driven by Information and Communication Technologies. Contrary to what is widely assumed, the electronic city is not an automatic outgrowth of the "high-tech" modernist car city, but in fact connects much better to the more human-scaled 19th century city.

In order to discuss these purely geometric issues, it is necessary to have a clear definition of terms. I spend some time to define "fractal", "scaling", and "connectivity" in the more technical Appendices to this Chapter. Urbanists might incorrectly assume my title to mean: "Connecting the disconnected city". Yes, contemporary cities are disconnected, but in a separate sense, they are also not fractal. The distribution of the sizes of urban components and connections can define fundamentally different types of city. A picture emerges of a city made of distinct interacting networks, each of them working on several different scales. Though competing, these networks with very different character have to connect with each other, and cooperate in a seamless fashion to define a living city.

An enormous conceptual gain results from thinking of a city as a multiple fractal structure (Batty & Longley, 1994; Frankhauser, 1994). As urbanists, we free ourselves from the misleading term of a "defining scale", since a fractal exists on all scales. Different urban processes and mechanisms act on different scales. The notion of events happening at all scales and cooperating in some intrinsic manner across scales facilitates an understanding of how a city lives and grows, and makes planning a less haphazard affair. This Chapter shows why historical cities are fractal, whereas the twentieth-century city is not. The city of the future has to become fractal again. It's going to do this by adapting the relevant geometrical solutions from traditional cities, while incorporating new fractal structure appropriate for new exigencies and new technologies.

I begin this Chapter by describing what type of city is fractal, and what type is not. The key idea is the existence of linked structure at all scales in a hierarchy, from the very large to the very small. For more technical details, one should read Appendix I. I then outline the connectivity that makes a city alive. Living cities have a vastly larger number of connections between nodes than one expects from the modernist city. For such connections to

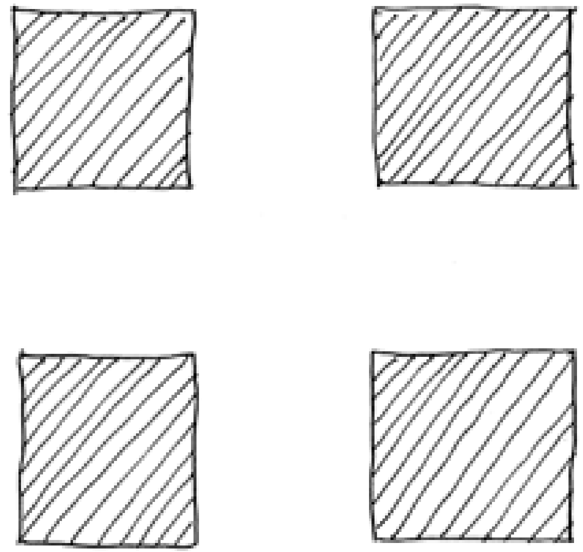


Fig. 1 Plan of a non-fractal modernist city.

develop naturally, they require an enormous variety of nodes in close mixing. Monofunctional zoning – the pivotal notion of CIAM urban planning – is thereby shown to prevent life in a city (Figure 1).

The rest of the Chapter discusses the hierarchy of connections necessary to sustain urban life. Competing networks of connections exist on several scales, each scale being necessary for separate functions. Understanding these interconnections is essential if we wish to incorporate the electronic city into the physical city. I criticize the policy of eliminating small-scale connections in favor of large-scale connections – the city needs both, and in the proper balance. Today's cities have an entirely inadequate interface between the car and pedestrian realms, and I recall proposals by Christopher Alexander that solve this problem. Next, I discuss the efficiency of networks, introducing the idea of 'small-world' networks.

There is a major gap in urban thinking – the lack of an epistemological framework in which to verify whether urban interventions actually lead to the intended effect, or whether they instead degrade the urban fabric. Determining the causality of urban actions (i.e., what causes what) is essential before we act. I call for a more intelligent, scientific approach to urban intervention. The Chapter concludes with suggestions on how to regenerate the urban fabric. My proposals include using ideas of Christopher Alexander and Léon Krier to re-establish the pedestrian network, guided by our recent knowledge of the structure of the World-Wide Web.

Three technical Appendices go into more detail in describing the mathematics of urban form. First I discuss fractals and scaling, showing how a fractal is in fact a sophisticated connective structure across scales. Second, I present the distribution of sizes, which tells us how many pieces exist of a certain size when they follow fractal scaling. This result applies to the size of neighborhoods, buildings, urban spaces, green

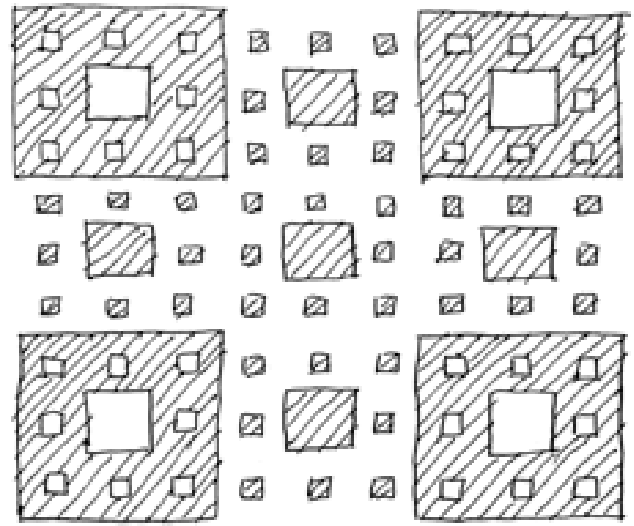


Fig. 2 Plan of unrealistically ordered fractal city.

spaces, roads, and paths. Third, I discuss what sort of physical size distribution is compatible with electronic connections. From a mathematical point of view, the electronic city connects best to a traditional city that includes pedestrian connections, and this result is corroborated by evolving patterns of the spatial/electronic interface.

What type of city is fractal?

Only older, pre-modernist cities are fractal, because they work on all scales. Mediaeval cities are the most fractal on the smaller scales up to 1 km, whereas 19th century cities work better on larger scales. Urban typologies used throughout history up until the twentieth century lead automatically to a fractal structure (Salingaros, 2001) (see Figures 2 and 3). Traditional urban form follows the pedestrian transportation web. The predominantly pedestrian city was built over time – with continuous incremental additions – on a fractal model, without its builders being aware of it. As I have argued elsewhere, the human mind has a fractal model imprinted in it, so what it intuitively generates will have a fractal structure (Mikiten, Salingaros and Yu, 2000).

People actually have to be psychologically conditioned before they can create non-fractal objects. Unfortunately, that is just what our education and media have been doing to us throughout the past several decades. The "image of modernity" is one of sleek, abrupt geometric shapes, and this is perhaps the most powerful force in shaping our cities. Never mind that it has nothing to do with how a living city works and functions – the simplistic image is what drives us to build. More alarming, it is also what decides which pieces of existing fabric to destroy as being "no longer up-to-date". We have adopted a set of selection criteria that are irrelevant to urban life, and destructive to the urban fabric.

The ideal city of Le Corbusier is a purely large-scale conception, hence non-fractal. Its components are skyscrapers, highways, and vast paved open spaces. Le Corbusier drew

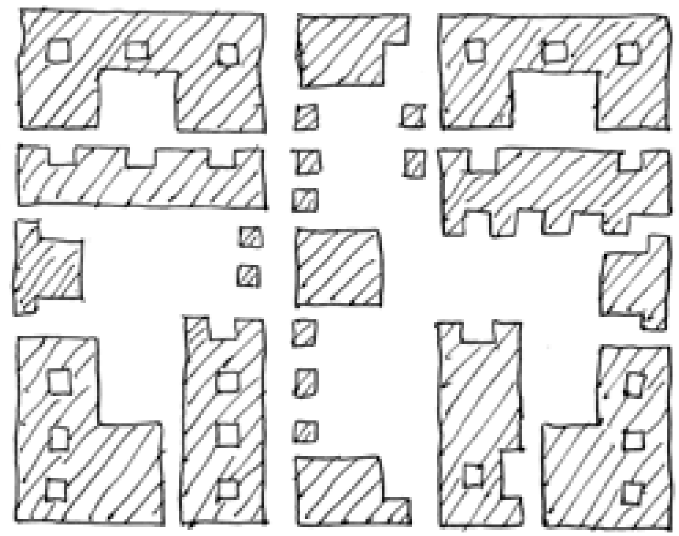


Fig. 3 Flowing geometry of the city defines urban space.

skyscrapers sitting in a giant park, everything being defined only on the two or three largest scales. There is little distinct structure seen on the infinite range of scales below the width of skyscrapers, and certainly nothing on the human range of scales 1 cm to 2 m. He missed the necessity of all the smaller scales in a living city. Le Corbusier totally misjudged what his "city of the future" would look like. His skyscrapers did indeed replace the traditional living urban fabric, but they don't sit in giant parks – urban forces dictate that they instead sit in huge parking lots.

Haussmann's intervention in Paris, on the other hand, can be explained by fractal scaling. When Mediaeval Paris had grown beyond a certain size so that its narrow streets could no longer support traffic, it became necessary to add structures on a new, larger scale. Thus, it became necessary to destroy some urban fabric in order to cut longer/wider streets into the city. Pope Sixtus V did the same to Rome. The same process was behind the introduction of large urban parks – once the city has extended beyond a certain geographical area, there is a need for a larger green space. Examples of great nineteenth-century parks that replaced urban fabric are to be found in all major cities. In the twentieth century, however, these large-scale urban interventions (roads and parks) were misunderstood, and only their destructive aspect was copied as a model.

Urban morphology is a product of the particular transportation system laid down by the government when the city was initially built. Later modifications to the transportation system lead to changes in city structure. Today, governments lay down exclusively car cities (by legislating the road network and infrastructure before anything can be built), or come in and destroy an existing pedestrian city in order to transform it into a car city. In the second instance, pieces of the old pedestrian city might survive to provide at least some remnants of urban life (if the state machine is truly efficient, nothing will be left). For this reason, it is extremely difficult to transform a post-war car city or suburb into a pedestrian city – one has to rebuild a new pedestrian network into the car city.

Contemporary architecture – including those styles reacting to minimal modernism – remains anti-fractal. The reason is that it rejects organized complexity on the human range of scales 1 cm to 2 m. Postmodernist and Deconstructivist buildings, with only a few exceptions, have inherited the ban on pattern, ornament, and decorated materials and surfaces. Their vocabulary consists of high-tech materials and "pure" surfaces, and their structural language is incoherent. As long as a city's structural and connective hierarchy is missing all of its lower scales, the city is not fractal. Despite misleading claims by its proponents, the intentional disorganization characteristic of the deconstructivist architectural style is the opposite of the internal organization of a true fractal.

Connectivity and the urban web

A city's life comes from its connectivity (Dupuy, 1991). All the geometry does is to facilitate the support of a connective web so that human interactions can occur. These are the reason people chose to live in cities in the first place. We need to discuss the connective properties of random graphs to gain some insight into how city life arises (Salingaros, 2005). First consider how connections form. Each connection takes place in order to carry out an information exchange between two nodes (Castells, 1989; Meier, 1962). This information could be encoded in goods. For example, a person needs to go from his house to his office. These two nodes are "house" and "office", and they need to be connected. A physical path structure must facilitate this interaction, otherwise the person cannot function.

Nodes will connect via paths in an entirely abstract manner. Suppose we start with no connections at all, and then randomly connect pairs of nodes, one pair at a time. We don't try to connect all of them deliberately – each time, a connection is established at random, and may even link two nodes that are already connected. An important mathematical result, due to Erdös and Rényi, states that after a certain number of connective steps, a majority (that is, more than 80%) of the nodes will connect rather suddenly (Barabási, 2002). This is due to the formation of several connected nets of nodes, which grow with successive steps. At the threshold established by Erdös and Rényi, the hitherto separate nets will connect together into one giant net, thus linking most of the nodes together (Figure 4).

The relative number of connections establishes how a living city works (Alexander, 1965). Deliberately connecting N nodes in a minimal way so that two nodes are connected pairwise via one link requires $N/2$ paths (Figure 5). That is, half the nodes are houses, and the other half are offices, and each house is connected to one office. This is even less connected than a "tree" type of graph (Alexander, 1965). The number of paths necessary to achieve random connectivity equals the far larger number $(N/2)\ln N$. With this number of paths, the majority of nodes are connected through intermediate nodes (Figure 4). Going even further, complete connectivity – where every node is connected DIRECTLY to every other node without going through any intermediate nodes – requires $N^2/2$ paths (for large N) (Figure 6).

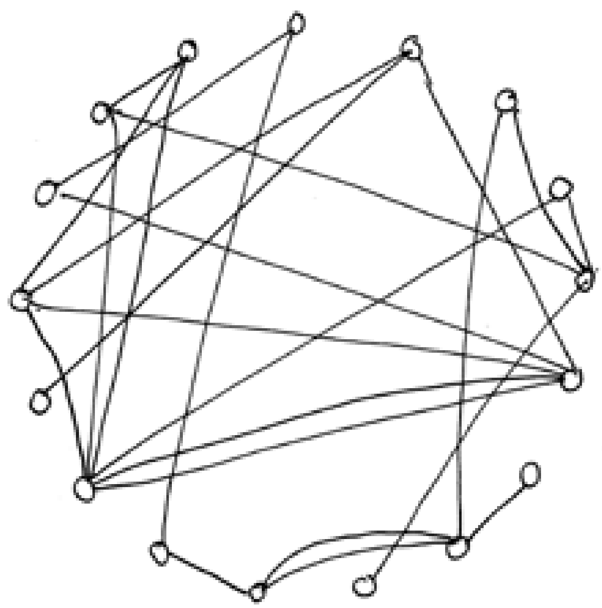
Applying these results to a city provides lower and upper bounds for the required number of paths. Urban life is the interaction made possible when the nodes in a city are connected to each other, either directly or indirectly. We therefore expect that a living city with N nodes have somewhere between $(N/2)\ln N$ and $N^2/2$ paths. In order to accommodate all of these connections, the transportation network must be multilayered. In addition, the infrastructure should be sufficiently fine-grained so as to allow many alternatives choices, which generate many alternative paths by permutation. This is the opposite of the postwar consolidation of numerous small urban blocks and streets into a few superblocks and superhighways, a process that severely reduces the number of available paths.

For a city, N roughly equals the number of people. Setting $N = 200{,}000$ gives us the following estimates for the relative number of connective paths. A modernist city of this size has 10^5 paths, whereas the randomly-connected city has 1.2×10^6 paths, or 12 *times* those in the modernist city. Furthermore, a completely-connected city has 2×10^{10} paths, or 200,000 *times* those in the modernist city. The mediaeval city was completely connected via direct pedestrian paths. We built such cities precisely so as to allow direct connections among all nodes, and our collective memory has never forgotten the personal freedom of movement and interaction that this gave us.

Our craving for direct car connections among every urban node makes the car city differ from the modernist city. The 20th century city is a combination of suburban car city and modernist city. In theory, we can connect by car directly to any other point, as long as there is parking, and no other cars want to use the network at the same time. The car increases a person's reach to tens of kilometers. Even more important is the transport and delivery of goods by truck. The price for car accessibility, however, is to sacrifice 50% of a city's surface to roads and parking, and to make our economies hostages to petroleum supplies. Le Corbusier wanted to amalgamate the paths in a modernist city (10^5 in our example) into one superpath (Salingaros, 2005). His method was to force all residences together into a few giant high-rise buildings, and all offices together into downtown skyscrapers.

Complementarity and catalysis

A fundamental principle is that *connections can only form between complementary nodes*. There is absolutely no reason for like nodes – having similar functional characteristics – to connect (Salingaros, 2005). Very little information exchange is possible among nodes of the same type. The forces that drive a city to function are generated by diversity and the need for information exchange between different types of nodes. Thus,



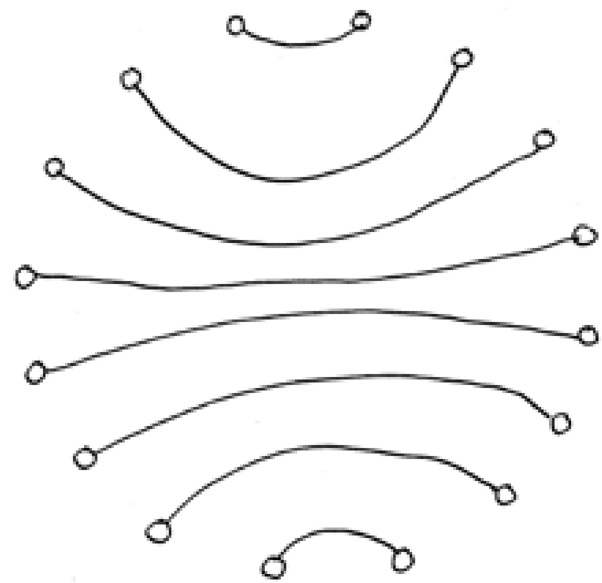


Fig. 4 Connecting pairs of nodes at random eventually connects most of them into one network.

Fig. 5 A pairwise-connected set of nodes does not define a network.

it makes no connective sense to physically group nodes of the same type into one geographical area. Homogeneous zoning of nodes into monofunctional regions forces non-interacting nodes into geometrical proximity for reasons such as profit for some developer, or the superficial desire for a simplistic visual order. It is antithetical to the basic rules for interactions.

Homogeneous regions that violate the above complementarity rule should not be confused with the coherence achieved by an identifiable neighborhood. In a neighborhood, a piece of a city contains sufficient variety and functions to become partially self-sufficient – at least to the degree that it occupies a specific geographical region. It could possess a particular social or ethnic character. The coherence resulting when every node is connected is a property of the healthy urban fabric, which supports, and is in turn supported by social cohesion. It is the opposite of persons and functions forced into one region either by misguided planning, or by economics, as in a dormitory suburb without commercial nodes, a slum of high-rise apartments without any stores nearby, or an office skyscraper without any residences nearby.

This brings us to catalysis. Many chemical reactions require some form of catalyst, otherwise the reaction rate is too slow to be efficient. Stuart Kauffman (1995) has studied a model in which a set of nodes achieves mutual catalysis to become an autocatalytic set. Each molecule also plays a role as a catalyst for reactions between others. The catalysts are to be found among the molecules that interact – there is no need to add catalysts if there are enough distinct molecular types. Kauffman finds that there is a minimum variety of different types of molecule that can be put together to define an autocatalytic set (the mathematics is the same as for the Erdös-Rényi theorem). Applied to urbanism, this implies that a city requires an enormous diversity of nodes in close proximity in order to be alive (Salingaros, 2005). Each piece of the urban fabric catalyzes interactions among the other pieces (Figure 7).

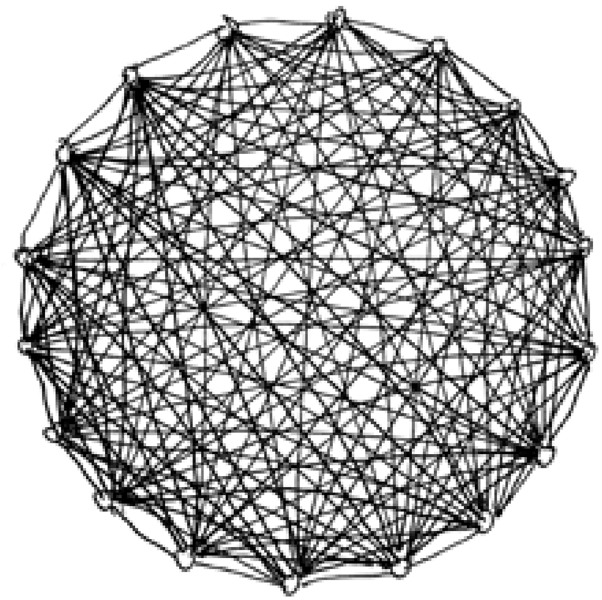


Fig. 6 A completely-connected set of nodes.

These results establish a picture of a multiply-connected urban fabric that works by autocatalysis. I will briefly sketch out two implications for the urban web. First, every node has to be given several alternative paths for connecting to another node. For example a person should have the options to walk, bicycle, drive a car, take either a public bus or jitney shuttle (private minibus), ride the subway, trolley, or connect electronically to another node. All except the last require physical linear connectivity, and therefore compete for space with each other and with the physical shelter for the nodes themselves. This quality imposes a flowing geometry on the city, which is radically different from the disconnected cubic visual geometry that defines the current architectural and urban paradigm.

Second, we must have sufficient density and variety of nodes so that they catalyze interactions amongst themselves. The vibrant 19th century city mixed buildings containing residential, commercial, light industrial, government, and religious nodes in close proximity to each other (Alexander, Ishikawa, Silverstein, Jacobson, Fiksdahl-King, and Angel, 1977; Krier, 1998). The physical structure of the city included the now missing anchors for urban space, such as wide sidewalks, boulevards, and street furniture. A restaurant catalyzes paths among residences, whereas residences in turn catalyze flow in front of the restaurant. All this is destroyed by cutting the connecting paths among diverse nodes (by erecting fences and barriers), and by concentrating similar nodes into homogeneous areas. We now give priority to the parking needs of the car city by building clusters of similar but unconnected nodes.

Hierarchy of connections

The internet offers exciting new possibilities for urbanism (Castells, 1989; Drewe, 1999; 2000; Graham and Marvin, 1996; 2001). It replaces many "dirty" connections that used to require enormous expenditures for fuel and infrastructure. While the

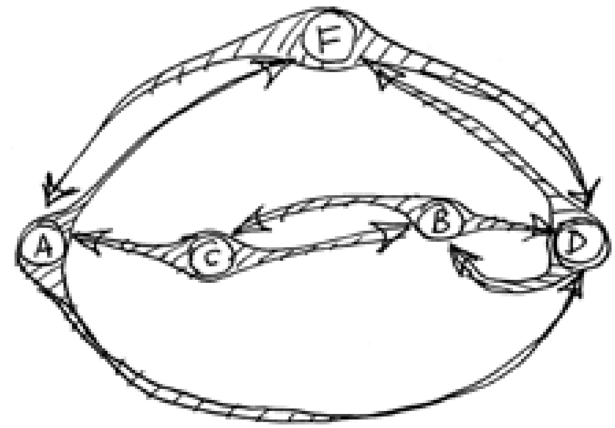


Fig. 7 Diverse elements catalyze connections among themselves.

dreams of some techno-urbanists of replacing physical transport with electronic telecommuting have not come to pass, the electronic web has indeed begun to merge with the transportation network. Here we face the paradox of the contemporary city – we do everything we can to connect virtually and by car, but we are disconnected physically on the pedestrian scale (Dupuy, 1991; 1995). Nevertheless, as we replace lengthy car journeys by electronic connections, the more valuable the pedestrian city becomes, though we have lost it in many places around the world.

Many problems of urbanism are ones of scale. A city needs to be connected on all scales. The particular types of connections that function at different scales are very different (Figure 8). Furthermore, since pathwise connectivity is most economical on a plane surface (the ground level), this means that different types of connections are going to compete with each other (Dupuy, 1991; 1995). A city has to balance all these connections. Like in any other problem of competition, the larger/stronger connections have the advantage, and will naturally displace the smaller/weaker connections. There exist fundamental physiological and psychological reasons for why pedestrians require small-scale connections on the ground level. Unless protected, those paths are at risk from other, stronger networks.

We have to be careful that large-scale connections are established strictly according to their place in the hierarchy. Failure to understand this process leads to appeasing transportation forces, which push for building more superhighways, while all the lower levels of the transportation hierarchy are erased (Dupuy, 1995). The transportation network – especially for small trucks – actually depends on connectivity and not on speed. Much smaller, narrower streets are needed to connect to the urban fabric – and in many cases, they need to be reintroduced as *woonerven* (narrow semi-pedestrian roads whose surface limits vehicle speed). The entire pedestrian city can again be built as a protected network interlacing with the sea of automotive traffic (Krier, 1998).

In most contemporary cities, the transportation network erases its lower levels in a misguided effort to become more "efficient". People demand instant access to an expressway, with homes and commercial sites right next to it. They want to skip the hierarchy of connections below the highest scale. Far too many highways are being built today, and far too many low and intermediate-capacity roads are being widened. Of course, the city and the number of cars are both growing, and will soon exceed any temporary new capacity. It makes no sense to be constantly upgrading the entire vehicular transportation network towards the higher scales, because that destroys the smaller scales.

Capillarity and fractal structure

My aim in this Chapter is to clarify the mechanisms whereby urban society connects on the neighborhood and street levels. I believe the connective structure on those scales to be fundamentally damaged. Only after repairing it can we adapt new patterns in network extension and accessibility. I wish to discuss this in terms of diffusion through capillary channels (Figure 9). Uncoordinated transport occurs via diffusion. Diffusion is not channelled flow – it is instead the random motion of particles at the smallest level. It turns into flow when all the small-scale movements are directed in the same direction.

In order to connect to another network, the elements that use the first network have to transfer through an interface into the second network. Where flow is involved, it has to *slow down* by entering fractal (i.e., progressively narrower) channels leading to the interface (Figure 9). By contrast, a network *speeds up* its flow by undoing fractal structure through streamlining. In the first case, geometrical constraints create a lowest level like the capillaries in the human circulation system, where the flow occurs at its slowest and most diffuse, though still fed by the circulation network. Capillarity is the opposite of rapid flow. At the highest

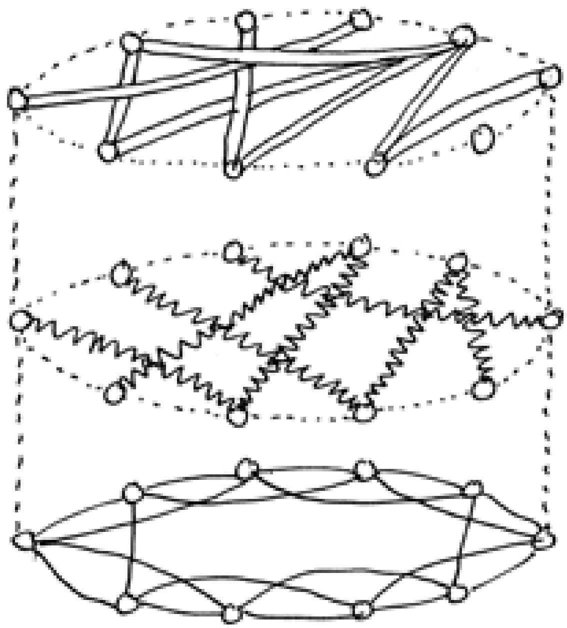


Fig. 8 Three different competing connective networks shown separated into layers.

level of the network, the strongest channels are wide and smooth to optimize rapid flow. A healthy network requires all levels from the very fast to the very slow.

Misunderstanding the fractal structure of urban networks, cities try to maximize flow everywhere, and in the process eliminate their capillary structure. An obsession with the largest scales in the car network leads to the disconnected urban geometry seen nowadays. The error lies in not recognizing the structure of linked multiple networks, which need to be fractal in order to connect to each other. They also need to be fractal to function properly by themselves, following the structural rules of complex systems (Salingaros, 2005). Early twentieth-century planners recognized the existence of several competing urban networks, but instead of figuring out how to accommodate all of them, they decided to get rid of those they considered “old-fashioned”.

The most glaring omission in contemporary cities is a totally inadequate car/pedestrian interface. Two networks of entirely distinct characteristics have to interface seamlessly without damaging each other. Christopher Alexander *et al*. (1977; patterns 11, 22, 32, 52, 54, 55, 97, 100, 103, 113) pointed out the fundamental importance of creating and maintaining this fractal interface, and offered practical solutions. Unfortunately, cities instead chose to follow CIAM’s opposite suggestions, as they worked very hard to erase their pedestrian network. The first step to destroying a system is to cut its entry points – i.e., its interface to other systems. The crossover between car and pedestrian realms was eliminated so that the pedestrian city could then be declared “redundant”.

The connective interface between people, green spaces, urban spaces, and built surfaces is just as important as the interface between cars and people. We connect most strongly on the most intimate scales (Mikiten, Salingaros and Yu, 2000; Salingaros, 2005). That’s the reason we love our cars – we touch their interiors, which in turn surround our body. Urban spaces

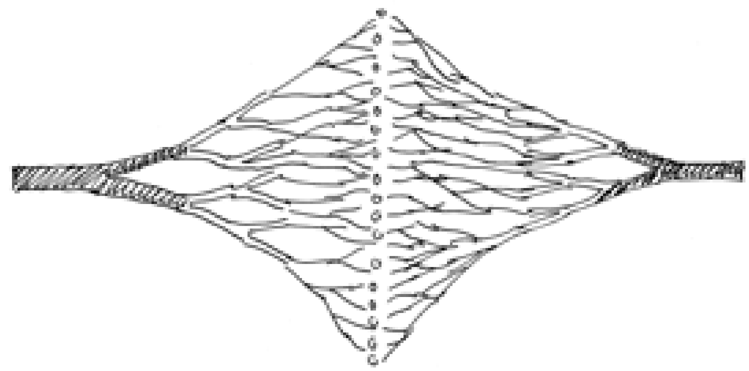


Fig. 9 Crossover requires capillary structure at the lowest levels.

(with or without green components) were meant to surround us with an inviting, comfortable boundary, but we have recently made them alien and hostile. *Without a spatial intimacy connecting us to the smallest scales, urban space is ineffective*. Following the dictates of a puritanical architectural modernism, we scorned spatial intimacy in today's cities as something "unmodern", and eliminated it.

Finally, we need to derive "patterns" in the sense of Alexander *et al*. (1977) for the emerging interface between the electronic web and the urban web. The advent of the electronic city is just as revolutionary as the growth of the automobile city (Castells, 1989; Drewe, 1999; 2000; Graham and Marvin, 1996; 2001). One consequence of this interaction is the proliferation of the "internet café" around the world. Note that this connection is via a characteristically pedestrian node. Physical intimacy in fact holds true for all entry points into the electronic city – the portable cellular telephone fits into one's hand, and the computer laptop fits on one's lap. These ergonomic designs integrate with physical connections on the human scale. Unlike the car network (but more like the underground Metro), we don't see the electronic web because it doesn't exist in any competing physical space.

Small-world networks and the World-Wide Web

In talking about connectivity so far, I referred to what is essentially the topology of connections. For much of the discussion, it doesn't matter whether the different paths are long, short, straight, or curved. We know from the distribution of sizes, however, that the paths are going to satisfy some distribution according to their length, width, or capacity (see Appendix II, at the end of this Chapter). It is now necessary to talk about the length of links so as to establish a hierarchy of connections according to their geometry.

A "small-world" network is one where nodes are connected by both long and short links (Barabási, 2002; Salingaros, 2005). Starting from a set of nodes with only nearest-neighbor interactions, add a few longer links at random. The result is a drastically improved overall connectivity (Figure 10). This is measured by how many links it takes to get from node A to node B for any two nodes chosen at random. If the nodes are connected only via nearest neighbors, then one is required to go through all the intermediate nodes between A and B. Just a few longer connections provide sufficient shortcuts to improve the connectivity. What has happened is that a system with only nearest-neighbor (shortest) connections has been transformed into one that is closer to having an inverse-power distribution of paths.

This is the same result discussed in Appendix II, at the end of this Chapter. The difference is that now we have started at the smallest scale and have built up to the largest scales. In urban structure, this progression corresponds to the dynamic growth of a village into a town, at which point it loses its initial small-scale connectivity. To regain it, it needs to cut new roads as "shortcuts" that connect spatially-separated regions. As it grows, a city requires larger and larger roads. *A network is always driven to adjust its communication infrastructure towards an inverse-power hierarchy*. This is the reason why the mediaeval city – with short-range pedestrian connections – could not survive unchanged.

For the same reason, however, the modernist city, which is artificially biased towards longer connections, was an unrealistic planning model. The car city that emerged in place of the modernist city requires many short car trips, hence parking lots everywhere. Contrary to what Le Corbusier decreed, people have never used their car to drive solely between their house in a garden suburb and their downtown office. The car is now used for every little chore of everyday life. Not surprisingly, once we have the sedentary connective freedom offered by the car, we demand a direct car connection to every urban node. This powerful force generates commercial suburbia, erasing the compact urban fabric in the process.

The web of public transport that includes subway, trams/streetcars, and light rail was an invention of cities growing rapidly in the nineteenth century. It became necessary to introduce shortcuts between regions of the pedestrian city that were too far apart to connect. The ideal solution was a superimposed transportation network that does not compete with the existing pedestrian and vehicular (early motor and horse-drawn) traffic, hence it was built either underground or raised overhead. The Metro should be interpreted as an extension of the pedestrian web, since it links regions of the city that are themselves parts of the *pedestrian* web. Altogether, it's a small-world network that improves its connectivity by introducing a few longer connections.

Failure to understand this causality (i.e., what action drives another action) has led to disappointment when car cities introduce a subway. Just because Paris has a subway, post-war commuter suburbs – with an existing road grid built for cars – unrealistically expect that a piece of 19th century European urban fabric will miraculously develop around new subway stops. This has failed to materialize. In a car city, the forces are overwhelmingly focussed on the need for parking around a metro station. Forces that would generate a pedestrian network are simply not present, and the actual needs may prevent any pedestrian web from ever forming there.

The World-Wide Web itself has grown and has self-organized according to a self-similar, small-world structure (Barabási, 2002). That is, it obeys the distribution of sizes that I discuss in Appendices II and III, at the end of this Chapter, this time for connective links (Figure 11). None of this structure has been imposed – it has all grown incrementally. Here we have an excellent example of self-organization, the process by which forces manage to act in balance to grow a complex system into a stable working structure. This process is analogous to the miracle of biological growth, as seen in the development of an embryo. A combination of code (in the DNA) and chemical fields leads to the formation of a wondrous complex whole.

When "small-world" networks were first introduced, it was discovered that the nervous systems of invertebrates (which are simple enough to be mapped) indeed obey such a distribution. The need for efficient signal connectivity via a nervous system has evolved exactly this type of network in animals. A city should evolve the same type of network connectivity, but unfortunately it cannot do this automatically. It is necessary to allow both self-generation of urban fabric on the small scale, as well as deliberate intervention on the large scale. This is in fact a central problem of urbanism – the competition between top-down imposed design, and bottom-up self-generated design. Both processes are misunderstood nowadays.

The bottom-up growth of short-scale connections allows for the free expression of natural urban forces. Left entirely to themselves, however, they will soon develop into random and incoherent structures, as exemplified in the *favela* or shantytown. The notion (and profession) of "planning" is a reaction to uncontrolled growth. And yet, there is an enormous degree of life that arises in such settings. Under the right conditions, the small-scale connections can be generated more or less spontaneously – all we need is some encouragement, guidance, and constraints to ensure a partially coherent form. Most top-down interventions today unfortunately destroy living structure. Cities need top-down planning, but it must be based on how the urban fabric grows and maintains itself.

Urban causality

Urban forces due to information exchange generate the urban fabric, just as other urban forces can degrade it or destroy it. A major unanswered question is – "*which forces cause which action,*

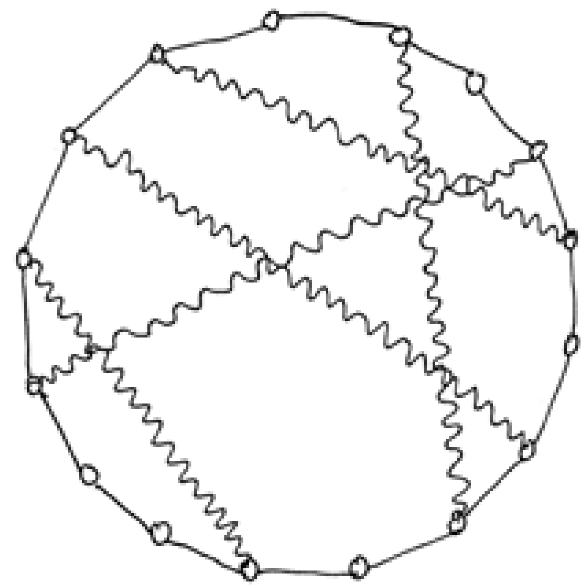


Fig. 10 A minimally-connected set of nodes with only nearest-neighbor links is made into a 'small-world' network by adding a few longer links.

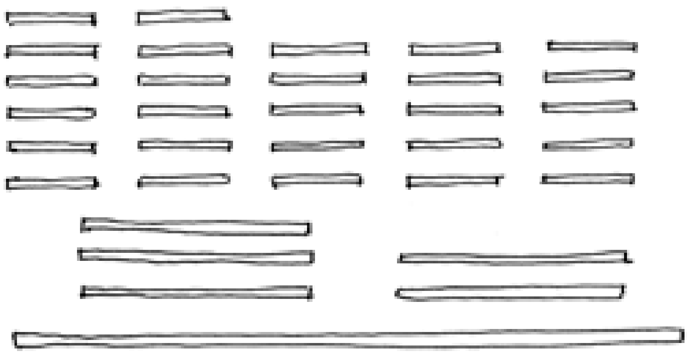


Fig. 11 Inverse-power distribution of sizes.

or conversely, what are the consequences of a particular urban action?" We can hardly expect to plan realistically unless we can anticipate the consequences of urban actions and interventions. Nor can we hope to understand how urban form arises if we don't grasp the character, strength, and causality of different urban forces. That topic of inquiry is still waiting serious investigation. Here I can only offer some preliminary thoughts.

Throughout this Chapter, I have tried to mention cases of urban causality that appear to be fairly clear. Some of these insights are unexpected, however, and run contrary to accepted wisdom. My approach has always been a scientific one – study urban actions and their consequences. I'm afraid that this is not standard urbanist practice. One could excuse this omission in part by saying that it is extremely difficult to isolate actions and their consequences, because of the complexity of the dynamic urban system. Nevertheless, we finally have sufficient scientific tools that allow a first approach to disentangling the interaction of urban forces, and establishing the mechanisms of urban causality.

I'm particularly worried about the occurrence of urban "viruses" that at first go unrecognized. By this, I mean a trivial or minor tool, idea, or practice that is introduced as harmless into the city, but which eventually destroys it. A historical example is the lead poisoning of Rome after the introduction of lead water pipes, as well as the practice of using lead as a preservative in wine. Perhaps we are facing similar pathologies today of which we are totally unaware. Governments carry out imaginary war scenarios with massive computer simulation (usually in secret symposia), trying to anticipate the worst disasters, and the consequences of even the most minor actions. They are doing the intelligent thing – planning ahead so that they will not be caught by surprise.

Why we eliminated the pedestrian city

We love a city when we can connect to it intimately. We retain a warm memory of that interaction. This memory consists of visual, olfactory, acoustical, and tactile connections. All of these memories can be formed only on the *pedestrian* level, far below in scale than the shortest walkable path. Our largely subconscious memory of a city is formed on a visceral level, on the physical scale of our own bodies. The "soul" of a city exists precisely on its smallest architectural scales. This turns out to include the "detritus" which modernism tried so hard to eliminate – unaligned and crooked walls, a bit of color, peeling paint, architectural ornaments, a step, a sidewalk tree, a portion of pavement, something to lean against, someplace to sit down outside, etc.

The anti-fractal movement of the twentieth century began with a call to destroy ornament. Architectural ornament is an intrinsic part of the entire city, however, and destroying it destroys one segment of the city's scales. Such an action erases the levels in the urban hierarchy spanning the scales 1 mm to 1 m. Soon afterwards, structures that anchored urban space – built structures ranging from 1 m to 3 m, such as kiosks, benches, porticoes, gazebos, low walls for sitting, etc. – were erased. Last came the elimination of sidewalks and the pedestrian connectivity of nearby buildings. What was left was only appropriate to the automobile city, not for pedestrian movement. True enough, it was necessary in the 1920s to accommodate the automobile into the 19th century city, but not to destroy the pedestrian city in the process.

There are two distinct, connected networks – the car city, and the pedestrian city. We have allowed the first to erase the second. That action severed human beings from their immediate environment. After living this way for several generations, human beings have accepted a disconnected lifestyle, even as they can never adjust to it physiologically and psychologically. Sadly, it is our own biological make-up that made us accept it. Being fundamentally lazy, we prefer to sit down in a car while connecting directly to nodes up to tens of kilometers away – there is no need to cross over to different modes of transport. Psychologically, we prefer moving about the city in our own personal (and personalized) spatial cocoon, rather than mixing with strangers in public transportation. We want to connect to a store, office, and our home directly and exclusively by car.

The pedestrian city has something important to offer, which offsets the advantages of the car city, namely – *an emotionally nourishing physical environment*. There is visual excitement, the joy of physical movement, the thrilling experience of vibrant city life, the sensory stimulation from urban space filled with other people of different types and different ages (experiences that are essentially different from the stresses of city driving). Le Corbusier despised all of this, and he went about eliminating it systematically via the CIAM planning rules. His books on urbanism espouse only the delights of driving around in a sports car. The elimination of urban space, connected green space, and the human scale from the urban fabric removed the unique set of forces that generate and support the pedestrian city.

Urban life requires a connected network of pedestrian urban spaces, whose sizes obey an inverse-power distribution (as outlined in Appendix II, at the end of this Chapter). A multiplicity of pedestrian paths is harbored and protected by open and semi-enclosed urban spaces. One cannot exist without the other. The network of urban space coincides with and supports the network of pedestrian paths (Krier, 1998; Salingaros, 2005) (Figure 12). Architects no longer design urban spaces that people wish to spend time in, however, and any built urban spaces are totally disconnected from the pedestrian network, hence from each other. This major breakdown in the concept of the city is not accidental – it is a straightforward application of a transportation geometry that is incompatible with urban space, as well as CIAM's prejudice against the concept of urban space itself (Salingaros, 2005).

Modernist prejudices for cars and against pedestrians have supported the unstated dogma that "motor vehicles don't threaten people", a denial of a fundamental psychological perception. So, instead of designing urban space that protects people from cars psychologically as well as physically, we continue to pretend that urban space is not necessary. The same hypocrisy gives priority to cars whenever car and pedestrian meet – the opposite of what ought to happen. A basic rule of living cities is that pedestrians must always feel safe from moving vehicles.

Human anatomy has scarcely frustrated Le Corbusier's dream of having wealthy people enter their car in the garage of their suburban home, and exiting it in their office's parking garage (on the other hand, the working class was supposed to get along with public transport). His vision of a city without a human scale has very nearly come to pass. Nevertheless, even in today's most disconnected, dysfunctional anti-city, people walk daily to and from their car. It is impossible to eliminate the pedestrian realm altogether. Since these short pedestrian paths are not supposed to exist, they are left geometrically ill-defined. The once glorious pedestrian city has contracted to dreary concrete parking garages and asphalt parking wastelands.

Green spaces and fractal geometry

This Chapter's ideas apply to the size and distribution of green spaces. A living city requires one very large green space, several ones of intermediate size, and very many of smaller size. In a city, there ought to be a distribution of public green spaces all the way down to tiny neighborhood parks for young children to play in, situated very near their house. This proposal is a theoretical verification of ideas originally proposed by Christopher Alexander *et al*. in "A Pattern Language" (1977; patterns 51, 60, 67, 111, and 172). The opposite practice of consolidation, following the myth of the "economy of scale", destroys the natural distribution of green spaces. Suburbs offer what was taken from our cities – a personal green space for each family (but they have problems with connectivity and low density).

Systemic connectivity occurs (or not) independently of the distribution of sizes. As evidence of our damaged cities, consider the present distribution and connectivity of green areas. It has become fashionable to put isolated pieces of ornamental green (lawn or bushes) in many useless places. While it is in principle good to have these green spaces, no-one can actually walk in them, because they are disconnected from pedestrians and from each other. They serve strictly as visual decoration for the car city, without relating in any way to the pedestrian city (which may in fact be nonexistent). The presence of green spaces of different sizes, even in an inverse-power distribution, does not create a network – they first have to connect on the human range of scales.

Nineteenth century cities worked very hard to provide a connective interface between the natural world of plants, trees, and rocks, and the built environment. This was achieved by means of geometry. Today, all we see is a geometry of disconnecting edges. A plant is an intrinsically fractal structure, however, and does not fit into the modernist machine geometry. Anti-fractal thinking is glaringly obvious in how the built environment is disconnected from plants. An unnatural geometry has been imposed on the natural world. Modernism prefers perfectly flat lawns and bushes trimmed into perfect cubes. Putting a tree into a square planter is a juxtaposition of two mutually exclusive and irreconcilable geometries.

Coming back to the idea of connectivity, green spaces fail in their urban function unless we can connect to them physically on a pedestrian level. Inaccessible lawn and trees, either because they are in the private domain, or because they are adjacent to a highway, do not form part of the urban fabric. These are not nature preserves, which require a degree of protection from pedestrians. We have become confused by the CIAM thinking embodying disconnectedness and segregation (not only in relation to green spaces, but in almost everything else having to do with the urban fabric).

Interventions to regenerate the urban fabric

The principal obstacle to urban regeneration is our society's philosophy of disconnectedness. Trying to introduce living urban fabric nowadays runs counter to most people's conception of order. We adopted an urban and architectural typology of nonliving forms in the twentieth century, and now this built environment has taught us a nonliving model of the universe. Our basic understanding of how the universe works is prejudiced by the built examples around us, as well as by an accompanying philosophy that falsely opposes modernity to traditional living processes. As a result, people consider surviving urban and architectural forms that embody life to be "impure", "oldfashioned", and even "reactionary". Within this prevalent worldview, it is extremely difficult to *recognize* living structure, which is a prerequisite for any interventions that aim to *generate* living structure.

I come back to the basic rule that urban morphology is determined by the city's transportation web. Faced with a dysfunctional city, innovative planning will be ineffective unless the transportation network and infrastructure are changed. That's very difficult to do, and, moreover, it's extremely expensive. Cities might not wish to undertake such a drastic reorganization also for philosophical reasons, since it implies changing their codes of growth corresponding to their "genes". Most cities around the world, however, did successfully change their genes to re-grow a car city out of an initially pedestrian city, so it is in principle possible to do the reverse.

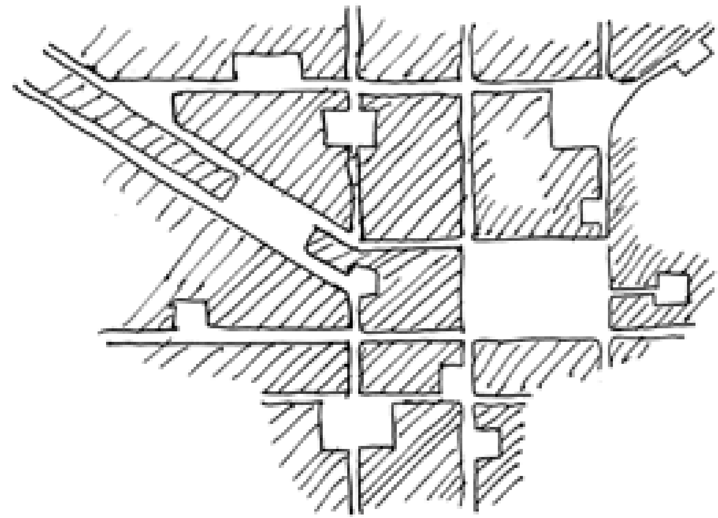


Fig. 12 Distribution and connectivity of urban and green spaces.

Urban regeneration today separates into two distinct problems – how to bring the car city to life, and how to revitalize dead pedestrian inner cities. In the first case, we have to build a pedestrian network inside the car city, erasing some of it in the process. Surprisingly, this goal can be achieved without seriously restricting the car/truck network. We need not sacrifice connectivity. The second case – the slum – is far more difficult to fix, since it is created by social problems driving out the healthy mixture of urban functions that define a living city. The people who live in an inner-city slum are disconnected from the rest of the city because of high crime, narcotics, and a lack of education and job skills. They lack long-scale social connections for information exchange.

I will not attempt to address the social problems that complicate urban regeneration in the inner city. Nevertheless, understanding one aspect of this complex phenomenon is almost trivially simple. People with very little power and influence should not be blamed for the urban problems the slum now poses. The more powerful economic classes just ceased to value the inner city as an urban environment, and absconded to the suburbs. Someone had to fill the vacated region, and, since no-one with any money considered it a desirable living environment, it was left to those with no other choice. In this interpretation, the slum dwellers serve an essential urban function, filling up regions that nobody else wants.

A combination of bottom-up and top-down methods acting together can recreate the pedestrian city protected from the car city, but connecting to it. The top-down method will legislate mixed-use zoning, and discourage concentrations of homogenous functions. Lower and upper density limits will select against tall buildings, as well as against sparse monofunctional dormitory suburbs. Above a certain minimum density (below which they would not be economically feasible), we can require a percentage of retail nodes to be mixed in with residences. Following the lead of the American New Urbanist Andrés Duany, we need to change the codes, and the city will then evolve towards living structure. The new codes will dictate that the majority of buildings are of mixed use. Tall buildings can be allowed in special situations, with the full understanding that the higher concentration is parasitic to its surroundings.

The other potential for life comes from natural urban forces. The bottom-up component of regeneration relaxes present codes so as to allow owner-built expansion. This is a random growth model that produces squatter settlements and third-world peripheral cities. It nevertheless represents a genuine living urban process that cannot be ignored. It should be constrained so it doesn't grow out of control, and channeling it is more intelligent than trying to eliminate it. Planners have learned (but will seldom admit) that this urban force CANNOT be eliminated entirely – uncontrolled growth will just occur outside the reach of the official agencies. It is far better to guide this creative force so as to build urban fabric that is more usable, hygienic, and permanent.

Regeneration in existing urban areas ought to be encouraged by offering subsidies for small-scale growth. This is the best and most efficient means of regenerating the smallest scales in cities, which are now missing. At present, the government subsidizes principally large-scale projects, following a planning philosophy of large-scale intervention. It is far easier to spend public money in large sums – a regrettable accounting feature of every government bureaucracy. That practice has to be modified, so that funds are divided according to an inverse-power distribution. This means handing out a large number of subsidies consisting of a small amount of money for small projects – the smaller, the better (Alexander, Silverstein, Angel, Ishikawa, and Abrams, 1975; Salingaros, 2005). Nowadays, building small things is almost universally discouraged, or even banned by zoning legislation.

Conclusion – the city of the future

If we can get over the ideological blinders imposed on the world by otherwise well-meaning but false ideas about "modernity", then we can begin to understand how the urban fabric forms itself and changes dynamically. We can then build new cities that incorporate the best characteristics of traditional cities, while utilizing the latest technology to facilitate instead of frustrating human interactions. At the same time, we can regenerate older cities, which already contain physical structures that would today be impossible to duplicate economically. Those buildings and urban spaces are being sacrificed to an intolerant design dogma, to be replaced by faceless and lifeless rectangular slabs, cubes, and parking lots.

Pathological components of the city can be selected against. Either an underconcentration, or overconcentration of nodes strains the infrastructure and resources of the city. Two extremes are suburban sprawl, and skyscrapers. Individuals desire the first, whereas governments and corporations want the second. Neither is acceptable. The first of these urban typologies uses up most of the automobile fuel in the city for the simplest transportation needs. The second typology concentrates non-interacting people into one building, drawing resources from the rest of the city. The urban forces generated by the overconcentration of a skyscraper tend to erase the urban fabric in a significant area around it. Skyscrapers feed off the rest of the city, and require more infrastructure and larger expressways to maintain them.

The electronic city offers help in two distinct ways. Firstly, it replaces many "dirty" connections of the older city, freeing up infrastructure and fuel consumption. It makes pedestrian pockets in the city much more attractive and practicable than ever before. Secondly, its very structure offers us a template to follow in rebuilding the urban fabric. I mentioned that the Internet follows the same structural laws as the traditional city. This should be enough reason to finally discard the misguided, simplistic twentieth-century models of urbanism that did so much to damage our cities.

If we need to connect the electronic city to a physical city, then the physical city must follow the same structural laws. By selectively applying successful prototypes from the past, together with insights from the science of networks, we can generate an entirely new type of living contemporary city.

Appendix I: Fractals and scaling

"Fractal" means "broken", yet that's not what the word denotes in mathematics. Very precise properties characterize a fractal, which are not usually understood by non-mathematicians. The key notion of a fractal is that it possesses structure on a hierarchy of scales. A structure defined at an overall size x implies something similar at a size rx, where r is a scaling factor like 1/3. For a structure to be fractal, there exist substructure at decreasing sizes r^2x, r^3x, r^4x, etc. A true mathematical fractal has self-similar structures going all the way down to the infinitesimal scales. For a physical fractal, the smallest scales become too small to see, so this implies a range of scales from very large to the very small.

The number r is called the "scaling factor", and can in theory be any fraction. In most common fractals it is usually some fixed number between 1/2 and 1/10. Naturally-occurring fractals (such as cauliflowers, fern leaves, and the human lung) exhibit a nested structure with r not very different from 1/3 (Salingaros, 1995; 2005).

There are two ways to construct a fractal as one goes down to the smaller scales. The first is to *add* substructure, while the second is to *subtract* substructure. In the first case, adding structure on every scale creates a folded, crinkled, textured object that is nowhere smooth or straight. A fractal "roughness" is generated on each edge. We have created the analogy to a catalytic surface, where chemicals can come together in close proximity to interact, drawn in by an attraction to the crinkled surface. In urbanism, an undulating urban boundary facilitates human interactions, as for example the edge of a piazza lined with shops and coffee tables (Salingaros, 2001). Urban spaces that are actually used are almost invariably enclosed by a fractal boundary. Removing the fractal structure by making the edge smooth removes the catalytic geometry for pedestrian interaction, and kills the urban space (Salingaros, 2005).

The other method of constructing a fractal is to create gaps at successively decreasing scales, like punching holes out of a material. The size of the holes gets smaller and smaller, forming a sieve or perforated membrane. In biology, membranes play just as important a role as catalytic surfaces do, since membranes provide the semi-permeable interface between distinct biological regions. In the same way, perforated urban interfaces allow pedestrian flow across an urban boundary, while preventing the flow of cars across the same boundary. Examples include colonnades, porticoes, arcades, small shop entrances, bollards along a sidewalk, etc. (Salingaros, 2001; 2005). The spaces between buildings are a fractal structure on the scale of the city itself. Enlarging the block size and constructing smooth walls without entrances are anti-fractal actions characteristic of post-war planning.

Fractals have another key property – that of coherence and self-similarity. This means that the different scales are related by some sort of scaling symmetry. In the simplest geometrical cases, a design is repeated at smaller and smaller magnifications, which serves to tie the different scales together into a whole. In a much more sophisticated application, processes and structures on different scales in a living city cooperate in an essential manner. Coherent structures on the large scale are made of components on the small scale. This is what unifies the distinct scales into an interacting, unified whole, both in terms of their geometry, and the dynamic processes occurring on those scales.

Appendix II: Fractals and the distribution of sizes

How many pieces of a city are there that measure a size *x*? These could be copies of the same type of object, or different objects of the same size. Assuming that a living city is fractal, then there is a simple answer – "there are *p* units of size *x*, where *p* is inversely proportional to *x*". That means that the smaller the urban components, the more numerous they have to be. The exact rule is called an "inverse-power distribution", and goes as $p = Cx^{-m}$, with C and m two constants that depend on the specific situation. Usually, *m* is an index between 1 and 2. (For those who wish to investigate this formula, *m* is the fractal or Hausdorff dimension). The other constant *C* is related to the largest size – in this case, the overall dimension of the city (Salingaros, 2005).

While the distribution of sizes is a continuous distribution (i.e., there is no restriction on the possible sizes), in combination with the scaling rule given previously, the distribution becomes discrete. We can label the scales by an integer *n*, with increasing *n* for smaller scales, and talk of the *n*th scale in the hierarchy. Let's illustrate this for a scaling factor $r = 1/3$ and fractal dimension $m = 1.5$. The distribution then becomes $p = C(x_n)^{-1.5} = 3^{1.5n}k$, with *k* a constant. For example, say that a city obeys such a power *n* law. There will be one structure – the city – on the largest size. Fix this overall size at 15 km for an illustration, which normalizes the constant *k* to equal one. Then, there will be 5 well-defined structures in the city of approximately 5 km in size, about 27 structures of size 1.7 km, and about 140 structures of size 556 m. These are the figures corresponding to $n = 0, 1, 2$, and 3 in the distribution equation.

The consequences of this distribution rule support earlier results by Christopher Alexander et al. (1977) and Léon Krier (1998). Our hypothetical city has organized into five main regions of about 5 km (the "cities within a city"). These have 27 subregions (boroughs) of about 1.7 km in extent. Finally, the urban fabric is defined by 140 distinct neighborhoods (the "urban quarter", or "community of 7,000") of about 556 m in size. Working out the consequences for the urban fabric leads directly to Alexander's patterns "Mosaic of Subcultures" (Pattern 8), "Subculture Boundary" (Pattern 13), and "Identifiable Neighborhood" (Pattern 14).

Theoretically, there should be very few structures of intermediate size to these. Of course, there exist urban structures of many different sizes, but the distribution implies a gap between the most obvious sizes. This means an improved definition of large-scale structures by means of an identifiable but permeable boundary – the opposite of today's amorphous suburban sprawl cut up by fences and barriers everywhere. If we don't find the above sizes applicable to the urban structure under discussion, then it is easy to find another distribution with new scaling parameters *r* and *m*. The same goes for the actual scales. If for practical reasons one requires structures at, say, 40 m and 1 m, then the hierarchy adopted must include those scales.

Another point is that the hierarchy continues all the way down in scales. For example, there will be about 20 thousand structures (buildings, urban spaces, green spaces) of size 21 m, corresponding to $n = 6$. Going down even further, the distribution predicts 531 thousand structures (architectural components, bushes, and street furniture) of size 2.3 m, corresponding to $n = 8$, and 387 million structures of size 2.8 cm (architectural ornamentation and natural detail), corresponding to $n = 12$. We could, of course, go down to 1 mm and below.

The importance of this discussion lies not in the specific figures given above for illustration, but in the picture they present. A fractal (i.e., scale-free) city has structural components at all sizes, from the size of the city all the way down to the dimensions of microstructure in the building materials. This conceptual approach unifies city planning, urbanism, urban space design, and architecture as merely different scales of one broad discipline. Perhaps the most revolutionary aspect of this theory is that it reveals the distribution of built structures to be naturally skewed towards the small scale, thus undoing the large-scale bias of twentieth-century planning.

Appendix III: Redressing network distribution

Telecommunications fits into the hierarchy of different channels of movement and information exchange in a city (Drewe, 1999; 2000). Having an effectively infinite number of electronic paths of zero physical length agrees perfectly with an inverse-power distribution. Recall (from Appendix II, above) the formula for the multiplicity $p = Cx^{-m}$, with m an index between 1 and 2. When the length of the path x becomes zero, then the number p of paths of zero length is infinite.

The introduction of Information and Communication Technologies does not redress the distribution of physical path lengths, because it is an independent network. In most cities today, there is a large gap where the shortest paths ought to be. This void in the network distribution can only be filled by physical paths that take less than 10 minutes to walk. Paradoxically, a scientific analysis of networks leads us right back to the traditional city (Krier, 1998). There is a very real danger, however, that people will accept the convenient zero-length electronic connections, and will not attempt to reestablish the missing pedestrian connections.

Even so, telecommunications has drastically altered the distribution of pathlengths towards the optimum. To see this, we need to analyze different physical network distributions. A good single figure that shows this difference is the average path length. In the first instance, the modernist city allows only a minimal number of longest-length connections, and no others. Its distribution of pathlengths is peaked at some multiple of the city's size x_0, say $(1/2)x_0$. It is heavily biased towards the longest paths, and therefore the addition of telecommunications partially satisfies a fundamental need for physical short-range connections. The distribution, however, remains distorted because of the large gap where the shorter physical paths ought to be.

In the second instance, the Erdös-Rényi model for a randomly-connected city gives a correct lower figure for the optimum path density, but an unrealistic average length. Its length distribution is also peaked at some fraction of the largest size, say $(1/3)x_0$ (Barabási, 2002). Because of the size of the contemporary car city, this distribution represents car connectivity, thus under-representing all of the pedestrian connections.

The third instance, which is what we want, is a scale-free city that obeys an inverse-power distribution. It has the majority of its connections on the smallest scales, so the shortest paths predominate. Label the shortest physical path – say, the distance from one connected building to another – as x_{min}. Then, this type of city's average physical path length is going to be something like $2x_{min}$. This average path length is shorter by orders of magnitude compared to the other two models. One could in theory (and in practice) continue to shorter (and more numerous) path lengths. Only in this scale-free case does telecommunications fit in neatly with the physical distribution of path lengths.

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