A Generative Method for Infrastructure Emergence

Kawandeep Virdee, Marco Lagi, Marcos Gaudiano

February 3, 2010

1 Introduction

Social systems are becoming more complex from technological advancements and increased connectivity. Individuals are further empowered with the capability to augment their memory and communication through computers, the internet, and cell phones. Every society has structures which influence collective behavior, and with all of the possible configurations of people in a population, the question emerges for designers of how to implement a method to use the collective information and create a successful design solution [1].

Cities have been shown to have fractal geometry. In this paper we show how the fractal shape can emerge from a generative process that takes information on the scale of individuals or groups, and uses it to design a permanent infrastructure on the scale of a city. In this sense, we grow cities consisting of individuals and roads, starting from just individuals.

2 Complexity and Design

Complex systems occupy a class of systems which is neither random, nor ordered, and exists somewhere in between both [5]. When looking at people within a society, it is evident they do not move completely randomly, as there are observable patterns of movement. However, the patterns are not so rigid as to bring to mind a fully ordered system, like a crystal lattice. When discussing ordered or random systems, it is useful to consider the amount of information described in a system. Information is a quantity that depends on the number of possible states of the system, mathematically parallel to the thermodynamic concept of entropy [6]. Lower information corresponds to higher order, and higher information corresponds to more randomness.

There are degrees of order and randomness in a complex system, and it is important to note that they also occur on scales. A marching band has low complexity on the scale of the individual, since the members of the band all move in step. On the larger scale, the band as a whole can have many configurations, so there is high complexity on the scale of the marching band. Compare the marching band to a group of people all randomly walking. On the individual level there is high complexity since there are many configurations at that scale, but on a higher scale there is less complexity, since all of the random individual movements average out. This is similar to an ideal gas , which consists of many random particles whose properties can be extended to describe the system as a whole. Complexity in a system is related to information and depends on the scale of observation of the system.

The notion of applying the multiscale view of society as a design method is essential given the degree to which products are made for the scale of many individuals in a system. Products in this sense are anything a designer creates to provide a service. Consider architecture, urban planning, political organization, and the internet as areas where a designer must include both the individual and the collective. It is widely evident that the success of Google among many other existing search engines was its ability to create a bottom-up algorithm that successfully used information on the scale of websites and their links. A complex problem at a scale requires a solution of equal or greater complexity at that scale [2]. The designer alone cannot create a successful solution since the complexity of the society far exceeds that of a single designer. The system of individuals exhibits a collective intelligence and self-organization upon which the designer can implement a method where the information given at the scale of the individual in society can be used to create the infrastructure at a larger scale. The designer creates a conduit to allow the self organization of the system to engineer a solution for itself. This becomes particularly important when considering that the impact a product has on an entire system may in turn affect the system's relationship with the product. If a designer can better understand the way individuals interact as complex systems, better products can be designed.

3 The Model

This model uses the information from a lower scale, that of the individual, to design at a higher scale, that of the city. The model explores the effect of having an agent simulation that contains two types of agents: ageless-immobile infrastructure, and mobile-ephemeral people. More specifically, a generative model is used to show the way in which infrastructure affects the growth of population, as well as city size over time. The model is constructed over the Game of Life model by John Conway. The Game of Life occurs on a 2-D grid where each square can be empty or be occupied (see Figure 1). The occupied cells can signify a region where there is life. At each iteration there are rules that determine whether or not a cell is occupied. The Game of Life is chosen because the occupied cells observe the characteristics of limited growth, while not completely disappearing. At the same time, from random initial conditions it is difficult to predict how the system will evolve. In our model occupied cells are designated *human*.

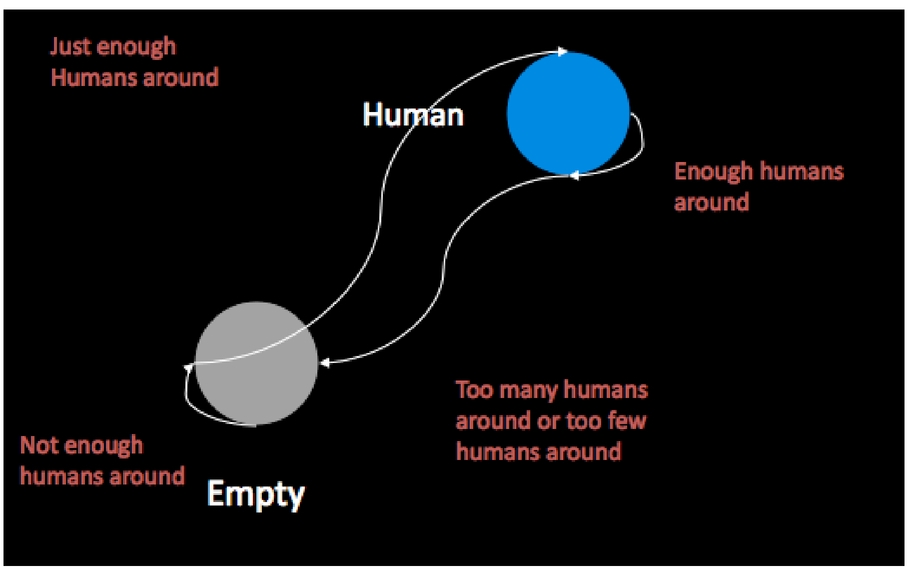

Figure 1: Cell types and rules of the classic Game of Life

For an empty cell, if there are three human cells around it, in the next iteration it will be occupied, else it will be empty. For a human cell, if there are less than 2 or more than 3 human cells around it, in the next iteration it will be empty, else it will be human (see Figure 2). This signifies a lower limit and an upper limit to the amount of humans around a human cell.

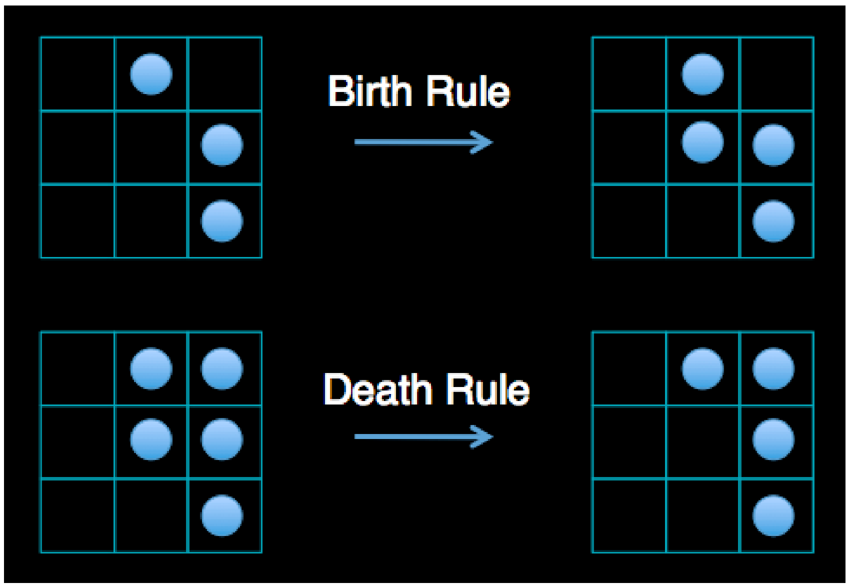

Figure 2: Examples of the birth and death rules. Each cell looks only to its nearest neighbors.

In the constructed model we add an additional state of the cell, which is *road* (see Figure 3). If there are enough humans around and few roads around, a road is initialized. The conditions are strict so that the whole terrain is not immediately covered in roads. To continue a road, the conditions are not as strict; Once a road is initialized, if there are enough humans around, further development will be made on the road. Once a road is constructed, it cannot be changed. A road counts as two humans to fulfill the minimum limit of humans around a cell for survival, and does not count towards the maximum limit.

In constructing the roads a mapping must be made that takes information from the scale of the human to the scale of a group of humans. The scale of the humans was just the nearest neighbor. The scale of the roads is much larger and can be varied.

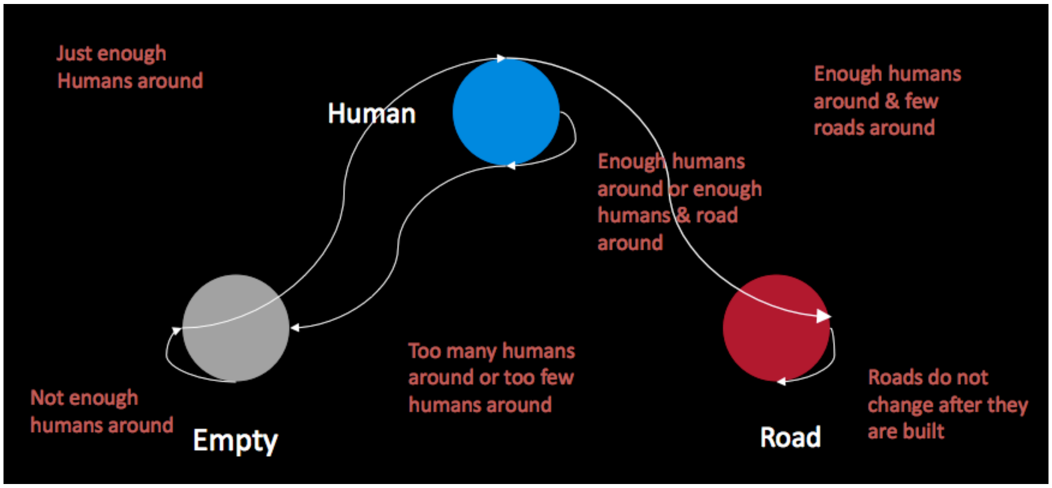

Figure 3: Extension of the Game of Life to include infrastructures.

A road is constructed if the number of humans in *range* minus the number of roads in *range-not* times a weight is greater than a *threshold* (see Figure 4). The number of roads is weighted so as to inhibit roads being constructed immediately next to each other, as it is more realistic to have separation between roads. The method for constructing a road is a scaled version of local inhibition long range attraction. In this case it takes as the input the results of the Game of Life simulation of the human agents.

A road will be build at a given (x',y') if

$H_{range} - A * R_{range-not} > T$

where H_{range} is the number of humans in distance *range* around (x',y'), A is a constant weight (15 in our model) and $R_{range-not}$ is the number of roads in distance *range-not* around (x',y') and T is the *threshold*.

Once a road is constructed, if there is an empty cell next to it, with exactly two human neighbors, one road neighbor, and less than two roads in *range-not* a road will be built in the empty cell. These requirements are not as strict is those to initially create a road, so the result is that it is far

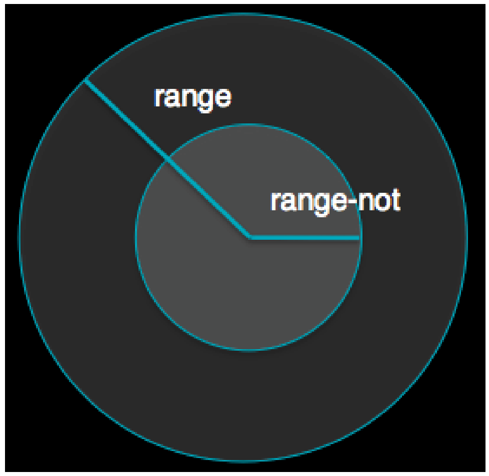

Figure 4: Parameters of the extended Game of Life: *range* and *range-not*

more likely infrastructure will develop along roads. Because the model is on a square lattice, it is more likely that these requirements will be met along a diagonal, which is evident in the infrastructure images. A road will be extended to a given (x',y') if the following are met:

- $R_{neighbor} = 1$
- $H_{neighbor} = 2$
- $R_{range-not} < 2$

where $R_{neighbor}$ is the number of roads around (x',y'), and $H_{neighbor}$ is the number of humans around (x',y').

After creating the model, many types of cities can be created by varying the parameters of *range* and *range-not* thus affecting the details of the local inhibition long range attraction behavior of the roads. Varying the three parameters (*threshold*, *range* and *range-not*) one can obtain different objects, as displayed in Figure 5.

The *threshold* is set high, and gradually decreased until roads first appear. If it is too low, roads will saturate the city. For small values of both

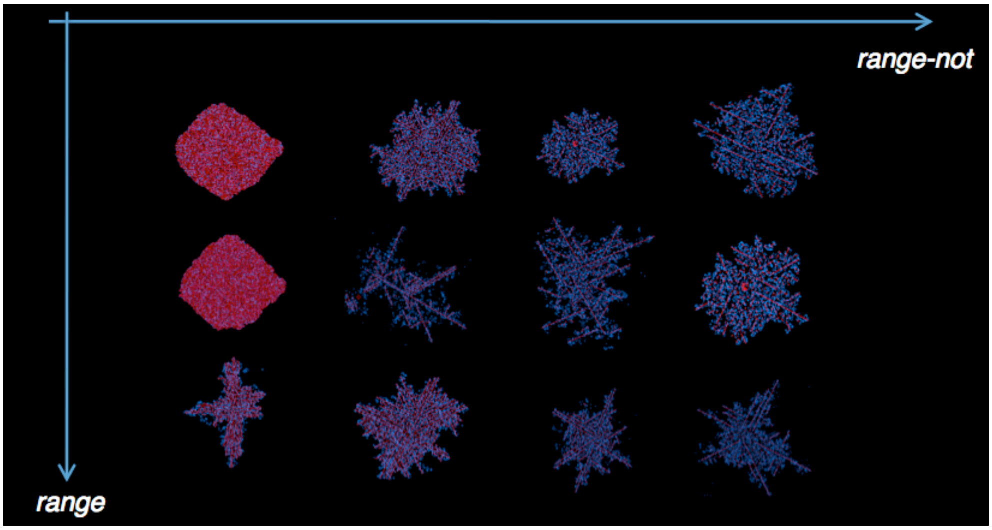

Figure 5: Varying the parameters of the model, one can obtain a wide variety of outputs.

range and *range-not*, the output of the model is an extremely dense mesh of roads. This liquid-like configuration of infrastructure is created since there is less local inhibition and roads cannot be removed once they are built.

Increasing *range* does not create a more realistic infrastructure, since *range* only affects the amount of humans counted; instead, increasing *range-not* has the effect of decreasing road density and of developing branch-like bifurcations. If both parameters are big enough (i.e. $range > 5$ and $range\text{-}not > 4$) we observed the evolution of an irregular and city-like geometric object, with self-similar properties and a fine structure. This is exactly the definition of a fractal object. We show in Figure 6 the results for $range = 8$, $range\text{-}not = 7$, $threshold = 23$.

4 Fractal Geometry

We applied the *box counting method* to calculate the fractal dimension of the cities we generated. The method simply consists of dividing the image in

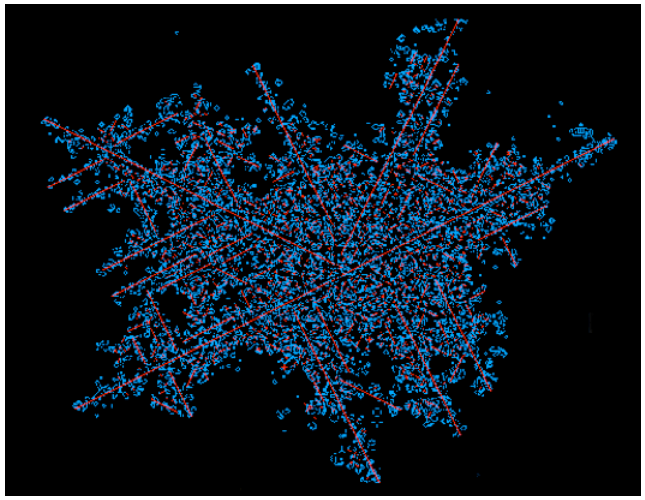

Figure 6: A city-like structure obtained setting *range*= 8, *range-not* = 7, *threshold* = 23 for our model. The fractal geometry is evident from the figure.

squares of edge ϵ, then counting the number N(ϵ) needed to cover the city, and compare log(N(ϵ)) with respect log($1/\epsilon$). For ϵ close to zero, a linear relationship arises, which has a slope D equal to the fractal dimension of the object:

$$log(N(\epsilon)) = Dlog(1/\epsilon) + B$$

where B is an irrelevant constant that depends on the figure and what one chooses as a unit of length [3]. We made no distinctions between blue (human) and red (road) pixels, so we only measured the fractal dimension of the whole object, which is composed of *non-empty* pixels. Let us apply the method to Figure 6: The linear fitting has a slope (the fractal dimension) of $D = 1.77$ for this case. We set $\epsilon = n/2^k$ for the calculations, where n is the edge-number of pixels of the image and $k = 1, 2, 3, 4, ...$ (see Figure 7).

All of our cities (obtained by varying the 3 parameters specified before) have fractal dimension D between 1.6 and 1.8. It is of interest to compare this value with real world data. The fractal dimensions of several US cities have been calculated in the past: the biggest dimension was found for the New

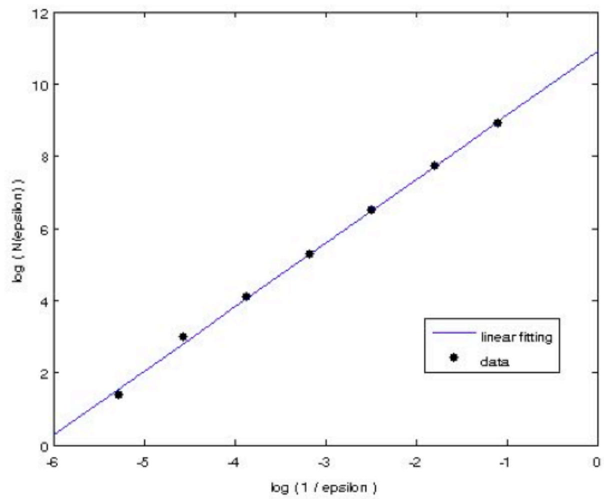

Figure 7: Results from the *box counting method*, taking Figure 6 as an input.

York City case (NY, $D = 1.73$), and the smallest for Omaha (NE, $D = 1.28$) [4]. But it is also known that the fractal dimension of a city is a function of time: a younger city has a smaller D than an older one. Baltimore, MD for example had $D = 1.02$ in 1822, that grew up to $D = 1.72$ in 1992. Our model shows the same results, as displayed in Figure 8 (the time frame is arbitrary).

5 Conclusions

It has been shown that real cities grow like fractals. Our goal was to find a model with a simple set of rules that could reproduce this phenomenon. We modified the Game of Life introducing a new possible state for a cell, besides human and empty: the *road*. Varying just three parameters, the model is able to produce a wide variety of rough geometrical shapes, with fractal-like characteristics. These cities have fractal dimensions similar to real cities, that increase with time as the objects grow.

The relationship of population and infrastructure in the fractal cities created by our model is linear over time. In reality, population and infrastruc-

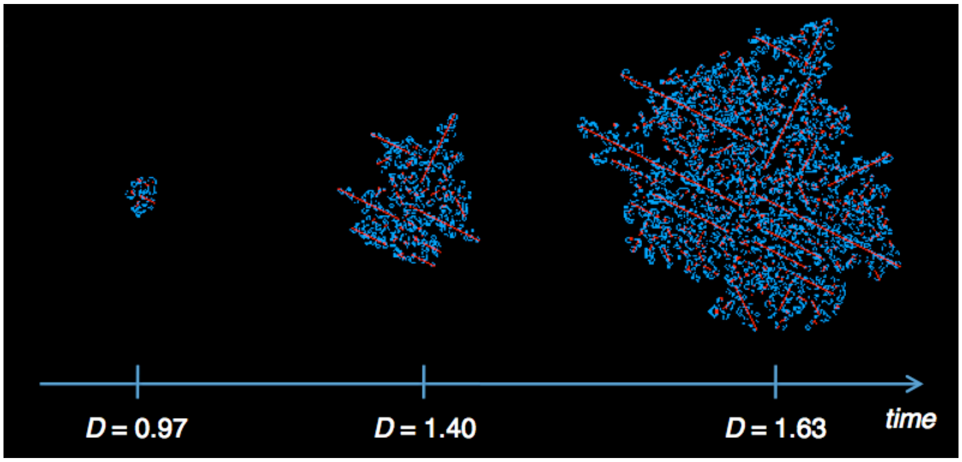

Figure 8: Time-dependence of D, the fractal dimension of the city. The time frame is arbitrary. D grows as the city expands.

ture are related by a power law, where the infrastructure grows less rapidly as population increases [4]. A reason for this is that there are limited resources in a city. A possible extension of the model would require the development of the structure in a realistic environment, where natural boundaries and available resources could influence the city growth in preferential directions, optimizing its design towards a high-performing geometry.

6 References

1. McCormack, J., Dorin, A. and Innocent, T. (2004) Generative Design: a paradigm for design research in Redmond, J. et. al. (eds) Proceedings of Futureground, Design Research Society, Melbourne.

2. Yaneer Bar-Yam: Making Things Work: Solving Complex Problems in a Complex World, Knowledge Press, 2005

3. B.B. Mandelbrot, The Fractal Geometry of Nature, Macmillan (1983).

4. Bettencourt et al. Growth, innovation, scaling, and the pace of life in cities PNAS, 2007

5. Miller, John H., Page, Scott. Complex Adaptive Systems: An Introduction to Computational Models of Social Life. Princeton University Press, 2007.

6. Claude E. Shannon. A mathematical theory of communication. The Bel l System Technical Journal, 27(79):379423,623656, 1948.