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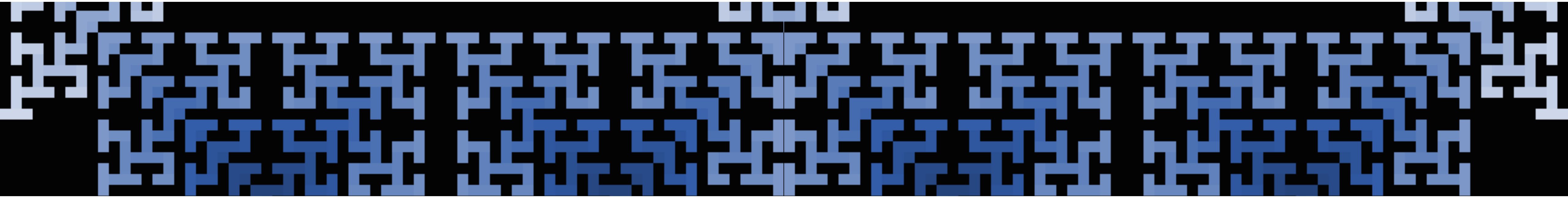
Cellular automata



GEOG-325: Applied Spatial Statistics and Urban Modelling

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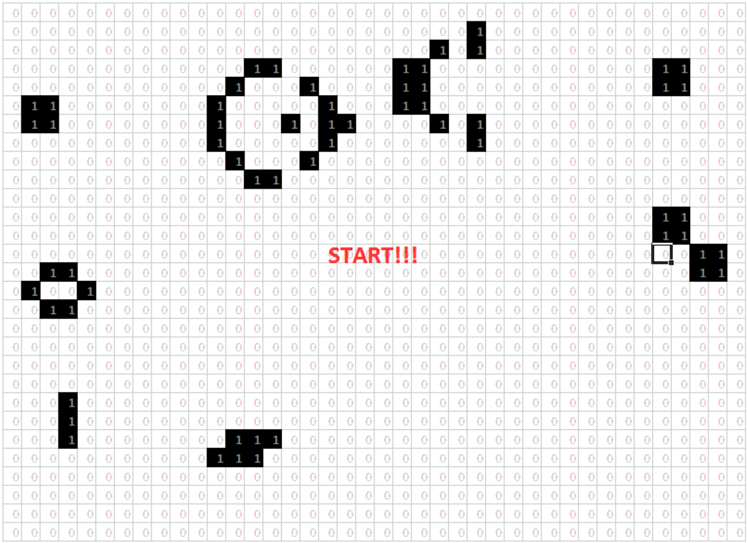
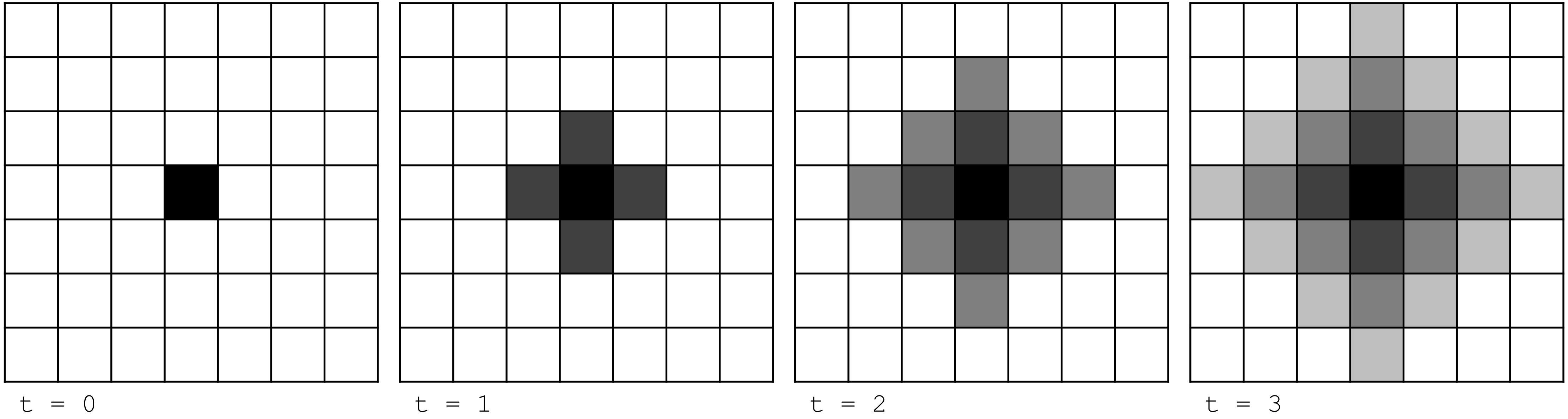
Cellular automata

- Cellular automata are founded upon the work of Turing (1952), von Neumann (1951), and von Neumann and Burks (1966) on **self-reproducing phenomena**.
- They help us understand the role of **atomic units** (cells) and **simple interaction rules** between these units in the construction and functioning of biological and physical phenomena.
- Complex systems approach: the **aggregate** characteristics of a system are entirely the **bottom-up result of local spatial interaction and spatial spillover effects**.



A different use of spatial connectivity [1/2]

- In most spatial statistics models, we assume a static situation and explore the ”final” neighborhood effects all at once, at one point in time.
- Now, assume a process in which cells in a lattice switch on (from white to black/grey), if the same switching happened to other cells in their neighborhood in the past.
- For instance, the 1st order von Neumann (rook) neighborhood:



The core idea of cellular automata

- A cellular automaton is a rule-based system that changes states in discrete time. A generic CA consists of the following elements:

- **Cells**: A set of contingent cells arranged inside an *n* by *k* lattice,
- **States**: The initial state of a cell and possible states to which it may transition,
- **Neighborhood**: A definition of neighborhood by contingency rules,
- **Transition rules**: A set of ‘if…, then…’ rules that determine a cell’s transition (or absence of) to a new state in time t+1 based on its state and that of its neighborhood in time t.

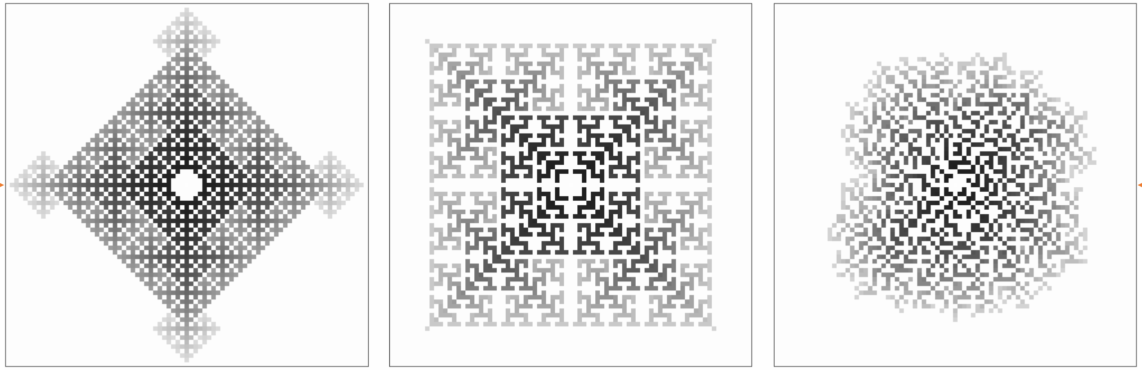
- CA contain what Batty (1997) calls the “generic development principle” of the evolution of spatial systems and which he describes as:
- **IF** *something* happens in a cell’s *neighborhood*, **THEN** *some-other-thing* happens to this *cell*.

CA in urban and regional planning

- Cells represent land.
- The initial and possible states are understood as developed (built-up) and undeveloped (natural) land.
- Neighborhood is typically defined as the von Neumann or Moore neighborhoods or modifications of those.
- Several specialized transition rules are usually involved.

A different use of spatial connectivity [2/2]

Batty (1997, 2007) demonstrates that different combinations of transition rules and neighborhood definitions, as well as the controlled introduction of randomness in state transitions, produces spatial forms that are affine to known urban morphologies:



Left: constrained growth with the von Neumann (rook) neighborhood (39 growth cycles).

Center: constrained growth with the Moore (queen) neighborhood (37 growth cycles).

Right: constrained growth with the Moore (queen) neighborhood and the probability of development is 50% (37 growth cycles).

CA models as theoretical experiments

- The majority of CA models do not represent real places.
- Spatial researchers use them to see how an initial state can evolve into various urban morphologies depending on the transition rule.
- This contributes to the development of theory in fields related to urban and regional processes, e.g. land use changes, spread/growth/diffusion of urbanization.

Recent advances in urban CA

- The objective is to enhance realism and detail in modelling growth and land use transitions in real-world urban systems.

- The main developments have been:
  - inclusion of custom-made cell states
  - introduction of a greater number of modelled land uses
  - ability to model particular urban growth drivers and mechanisms
  - inclusion of the transport network’s role
  - **ability to calibrate models with empirical data**
  - non-binary states and fuzzy transition rules
  - coupling with other simulation models

Operational value (Batty 1997)

- For operational urban and regional planning, CA represent a class of computer models with the ability to both:
  - reproduce observed urban morphologies
  - optimize those morphologies according to planning objectives [Batty 1997]

CA models as applied forecasting systems

- *If* a CA model can be developed so that the **historical** evolution of a real urban area is accurately reproduced,
- *Then* you can start asking questions from the model about **future** evolution, i.e. forecasting.

- Typical stages of setting up an operational CA model:
    - **Data**: collection and preparation of information about the physical (natural, human) and social environment
    - **Calibration**: setting the parameters of the model so that it reproduces accurately past growth; includes validation
    - **Forecasting**: predict (and map) future growth, based on historical behavior
    - **Scenario simulation**: predict how future growth looks like if this or that policy intervetion is applied

- Policy interventions studied with CA are typically **regulation** and **investment** in the areas of:
    - Spatial planning, e.g. zoning, land use
    - Transport planning, e.g. increased/reduced accessibility, new transport links
    - Environmental planning, e.g. regulation of natural amenities, regulation of natural hazards

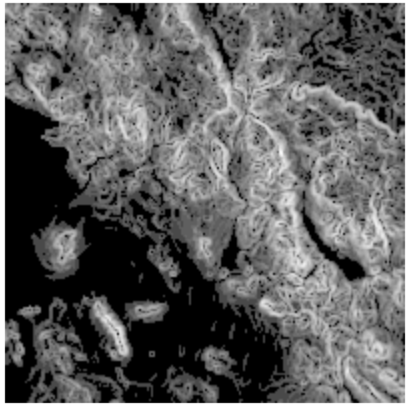
The SLEUTH model

- SLEUTH (**s**lope, **l**and use, **e**xclusion, **u**rban, **t**ransportation, **h**illshade) is a self-modifying CA model of **urban growth and land use transitions** developed by Keith Clarke et al. at the University of California, Santa Barbara (Clarke et al. 1997; Clarke and Gaydos 1998).

- It considers four drivers of urban growth: spontaneous; new spreading center; edge; road-influenced,
- And controls those drivers with five transition rules: dispersion, breed, spread, road gravity, and slope.

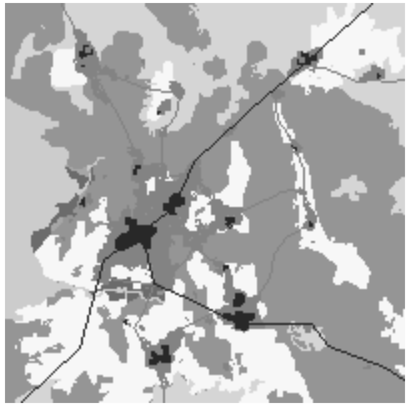
- Examples of model inputs:

slope



Topographical constraints

land use



exclusion

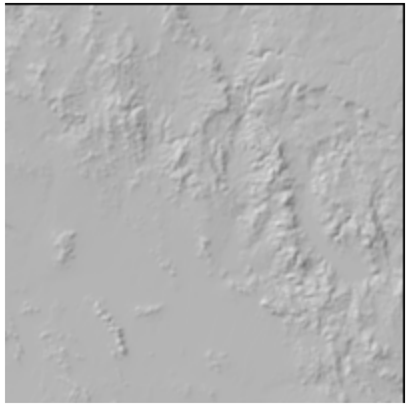
Planning constraints + water

urban/non-urban

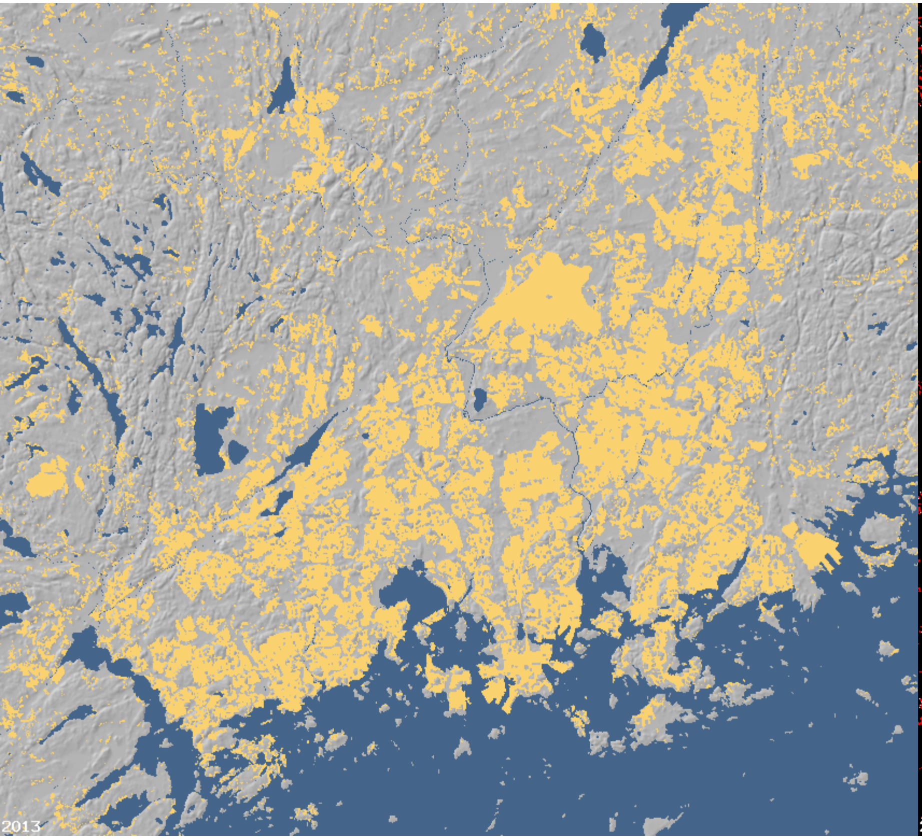
transportation

Accessibility

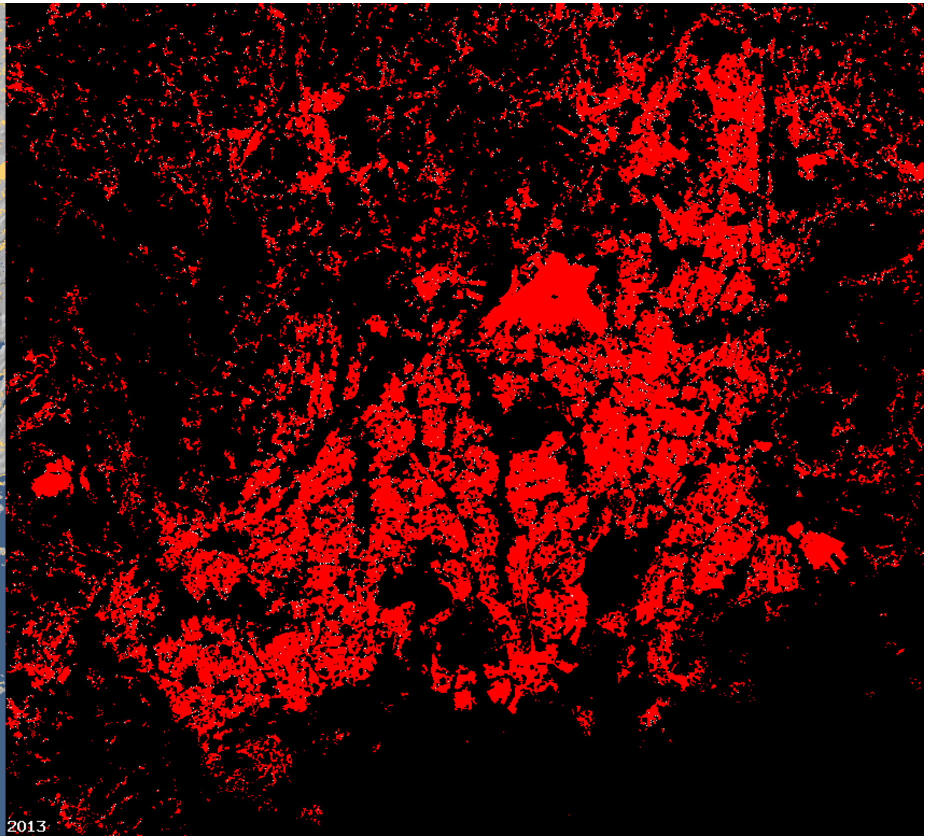
hillshade



Implementation in the Finnish capital region



probability of urbanization



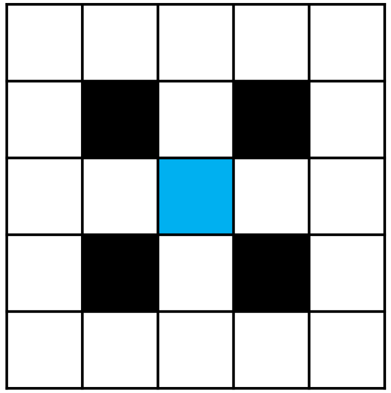
underlying drivers of urban growth

- Helsinki metropolitan area
  50 m, 2000-2040
- Validated and published at
  doi.org/10.1016/j.compenvurbsys.2017.04.005

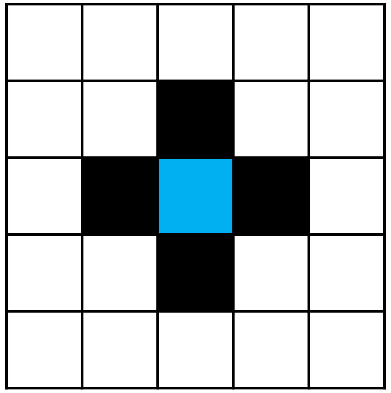
Fractals in urban studies

- The processes reproduced by CA are growth and expansion processes.
- As the “seed” grows:
  - it fills space additively,
  - in the manner prescribed in the transition rules
- Different growth dynamics leave a different signature.

- Such signature cannot be studied with Euclidean measures, e.g. density:



Dens. = 5/25 = 0.2



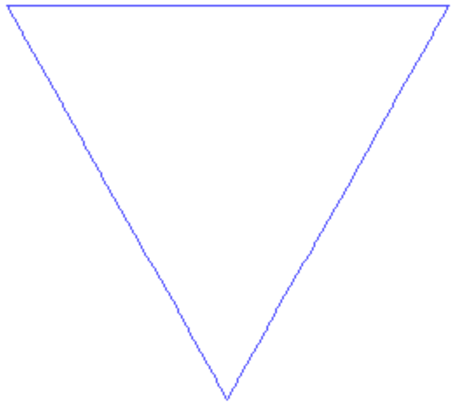
Dens. = 5/25 = 0.2

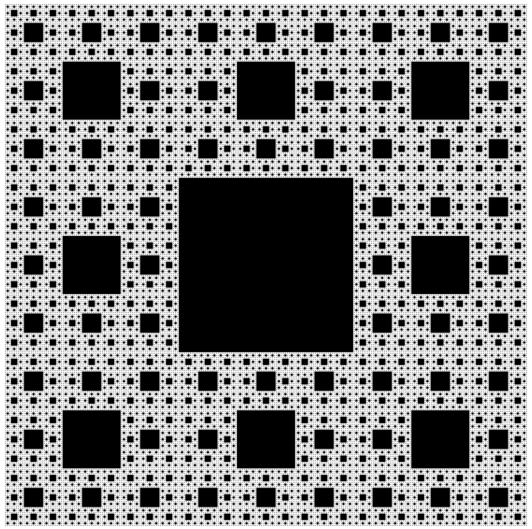
Fractals in urban studies

- Fractals are **mathematical sets** that, when visualized, produce shapes that are self-similar across scales (Mandelbrot 1982, 1967).

- A fractal entity **fills space in a self-replicating manner** because it grows in a multiplicative way, built additively from an elementary shape.

- It has been found that urban morphology shares properties with mathematical fractals.
- But instead of strict self-similarity, in urban studies we speak of **self-affinity**.





Fractals in urban studies

- Fractal geometry analyzes the generative structure and morphological characteristics of complex spatial systems. Oftentimes two attributes *x* and *y* of an object will scale with each other according to an exponent α (Batty 2007):

$$y = x^{\alpha} \ (1).$$

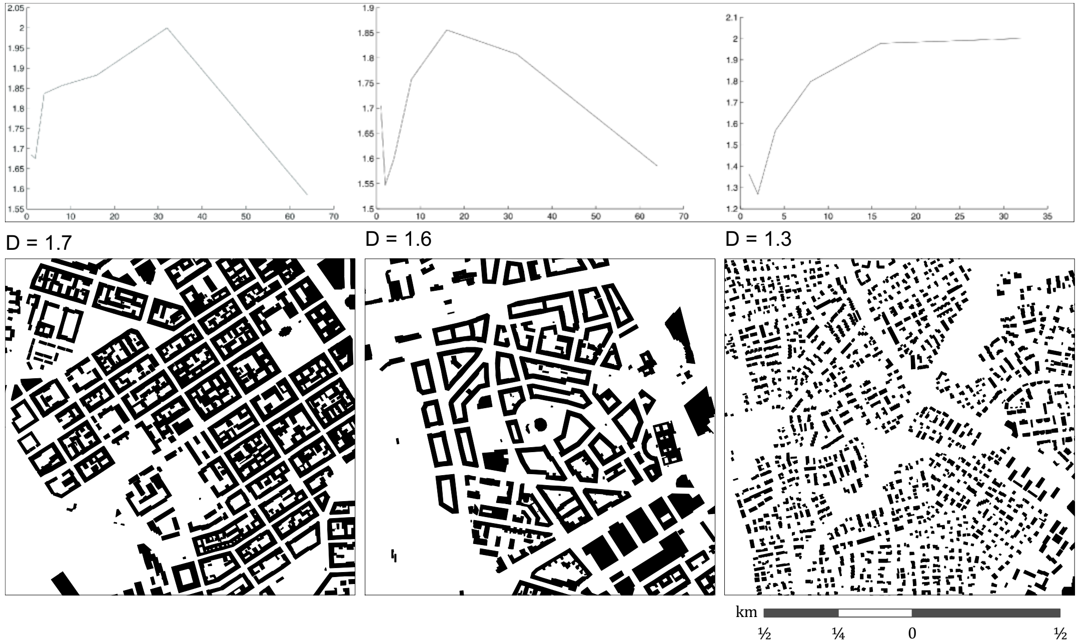
- This type of scaling behavior is often seen in growth processes characterized by constraints and competition and also characterizes many of the processes reproduced by cellular automata. As Equation (1) illustrates, scaling indicates that the percent change of attribute *y* is proportional, by a certain critical number α, to the percent change in attribute *x* (Batty 2007):

$$\frac{dy}{y} = \alpha \frac{dx}{x}.$$

Fractals in urban studies

- Count the number of pixels *N* inside a bounding box of size *ε.*
- Repeat by counting *N* in increasing *ε.*
- Estimate *N* as a function of *ε*: $N(\varepsilon) = \varepsilon^{\mathrm{D}}$.
- Parameter D is the fractal dimension, range = [0, 2].

- Assume that the fractal dimension D also depends on *ε.*
- This produces a series of fractal dimensions along a continuum of spatial scales: the “curve of fractal scaling behavior” (CFSB).
- The CFSB identifies changes in D from one spatial scale to another, i.e. changes in morphology at critical spatial scales.
- The CFSB of a given built environment is its spatial signature (Batty and Longley 1994).



Central (left, middle) and suburban (right) Helsinki.
Scale = 1:200000

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Questions for this session

- How do cellular automata see and explain the world?