The New Science of Cities

There are many sciences of the city

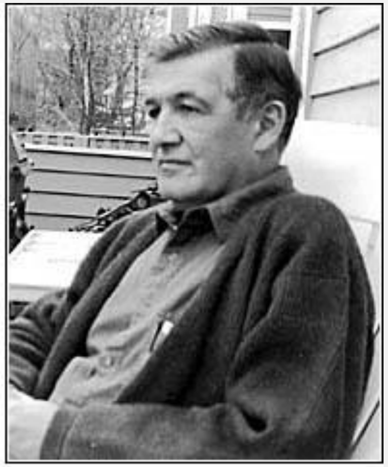
Michael Batty
Centre for Advanced Spatial Analysis (CASA)
University College London (UCL)

13th November 2019

m.batty@ucl.ac.uk
@jmichaelbatty

I have put this on my web site as a PDF and you can get it from

https://tinyurl.com/rpagr2b



William Alonso, 1933-1999

A theory of movements: I, introduction (Working paper - [Center for Planning and Development Research], University of California, Berkeley) Unknown Binding – 1976

by William Alonso (Author)

Papers in **Regional Science**

A THEORY OF THE URBAN LAND MARKET

William Alonso

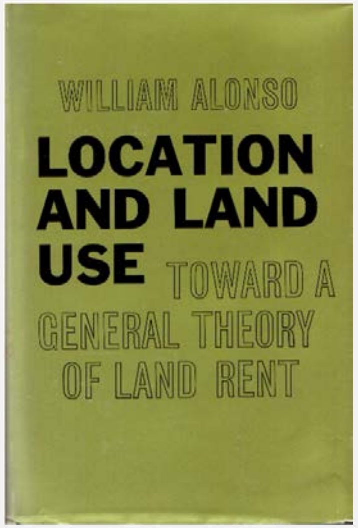
Issue

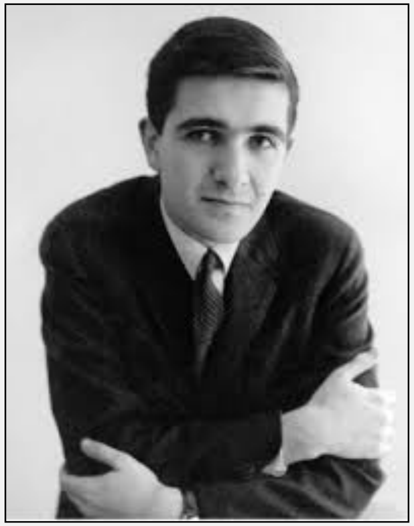
Article first published online: 14 JAN 2005

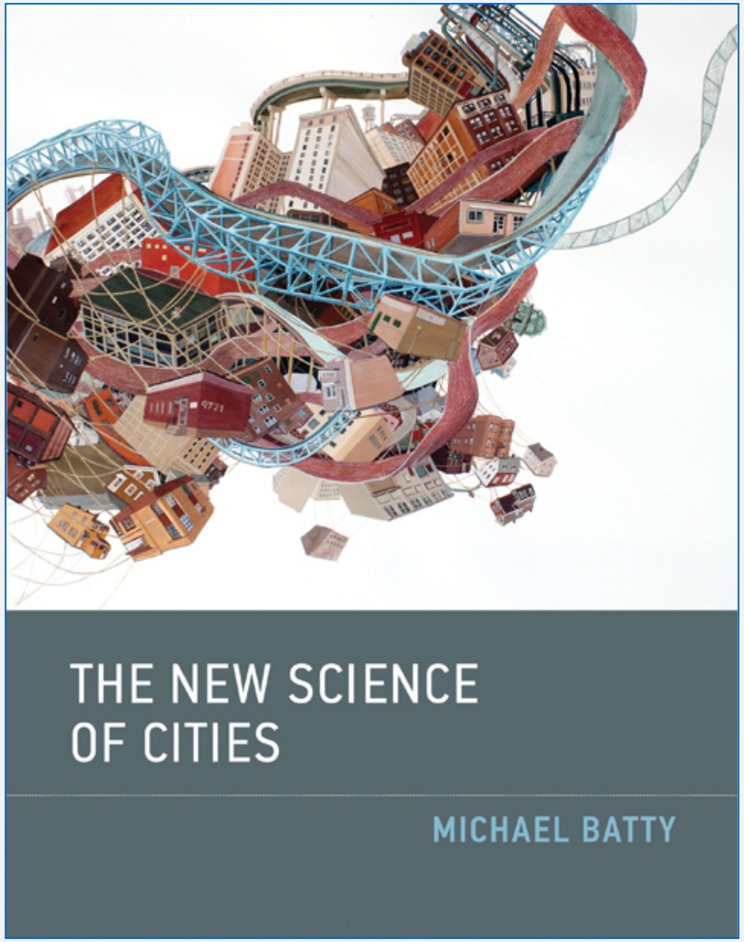
DOI: 10.1111/j.1435-5597.1960.tb01710.x

Papers in Regional Science

Volume 6, Issue 1, pages 149–157, January 1960







The MIT Press, Cambridge, MA, 2013

One of the Key Themes in the book

Location is no longer the key to explaining how cities function – it is ***Interactions***

- This is an old message – it was already on the agenda when regional science began. There was a famous book by Mitchell and Rapkin in the 1954 called **Urban Traffic: A Function of Land Use**. Networks and flows were the focus.

- Indeed Alonso' worked on these ideas which he developed in his **Theory of Movements** which he published in 1976

- The idea that we need to predict interactions from which emerge locations as a consequence of interactions runs throughout the book.

- A related notion is that we need to predict interactions as a consequence of two sets of objects which might be locations and activities or two different sets of locations – any two sets of objects that pertain to the problem and system in hand

- And from this we can construct **primals** and **duals** which are different conceptions of the same basic set of interactions. I don't think I have stressed these ideas enough in the book

- So in Part 1 of the book, I develop these basic ideas and in Part 2, I apply them to locational systems. This is really the **science of cities**

- In Part 3, I apply them to very different types of networks which are those used to explore how we as planners engage in **a science of design**

- So in this talk let me first develop the basic theme and after this move onto apply these to problem solving networks – to networks of how we as social agents in developing designs for locating new facilities in cities

So let us begin with two sets of objects – they might be locations defined by *i* and activities defined by *k*

$$\boldsymbol{X} = [X_{ik}] = \begin{bmatrix} X_{11} & X_{12} \dots X_{1m} \\ X_{21} & X_{22} \dots X_{2m} \\ & . \\ X_{i1} & X_{i2} \dots X_{im} \\ & . \\ X_{n1} & X_{n2} \dots X_{nm} \end{bmatrix} \qquad y_i = \sum_{k=1}^{m} \beta_k X_{ik} \qquad \boldsymbol{y} = \boldsymbol{X\beta}$$

$$P_{ij} = \sum_{k=1}^{m} X_{ik} X_{kj} = \begin{bmatrix} X_{11} & X_{12} \dots X_{1m} \\ X_{21} & X_{22} \dots X_{2m} \\ . & \\ X_{i1} & X_{i2} \dots X_{im} \\ . & \\ X_{n1} & X_{n2} \dots X_{nm} \end{bmatrix} \begin{bmatrix} X_{11} & X_{21} \dots X_{n1} \\ X_{12} & X_{22} \dots X_{n2} \\ . & \\ X_{1i} & X_{2i} \dots X_{ni} \\ . & \\ X_{1m} & X_{2m} \dots X_{nm} \end{bmatrix} \qquad \boldsymbol{P} = \boldsymbol{XX^T}$$

This defined the primal problem and the dual – two networks – the first between locations through activities, the second between activities through locations.

These are defined rather casually in terms of arraying the first matrix of locations and activities against its transpose activities versus locations to get the primal; and the other way around to get the dual

It doesn't matter what you call the primal or the dual

$$\textbf{\textit{The Primal}} \quad \boldsymbol{P = XX^T} \qquad \qquad \textbf{\textit{The Dual}} \quad \boldsymbol{D = X^T X}$$

Now in Part 2 of the book, I apply these ideas to locational problems – in particular to spatial interaction problems and networks of streets

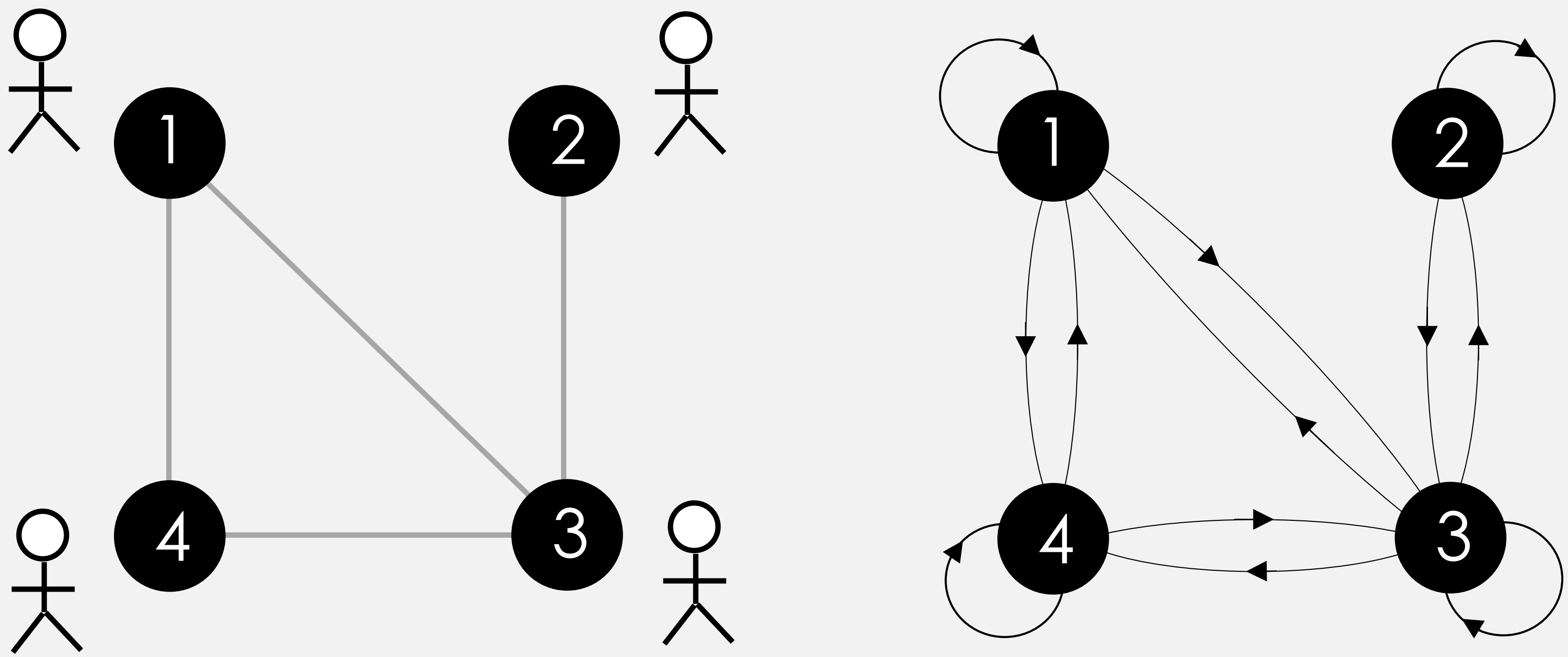
In fact there is a group in my own university who have specialized in defining buildings and streets at the urban design level as networks where one can see their problem of links between segments where segments are streets as defining accessibility between streets

In my terms here, this is the dual problem where one arrays intersections against street segments and you produce a network between the segments.

There is immediately a primal problem where we construct networks of streets from sets of nodes that define a street, but the guys in **space syntax** – for that is what it is called – don't do that but lots of people in network science have done this.

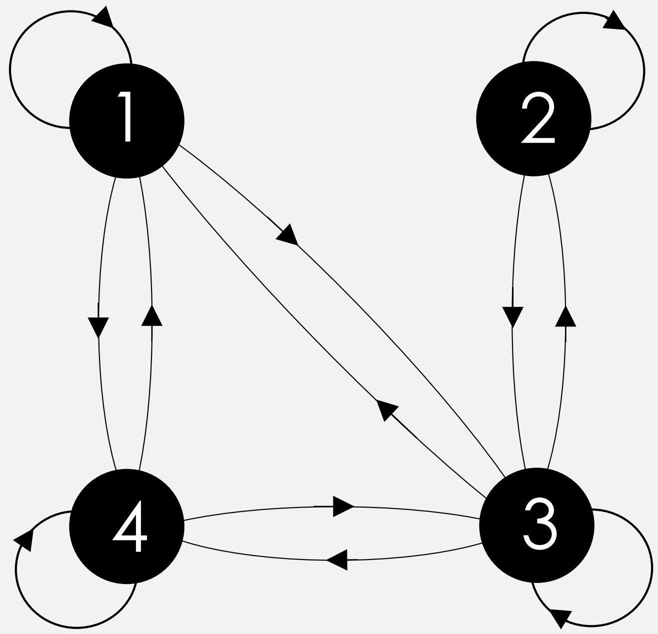
Now the second big idea in the book is that processes are defined on networks; many models in the book are so defined

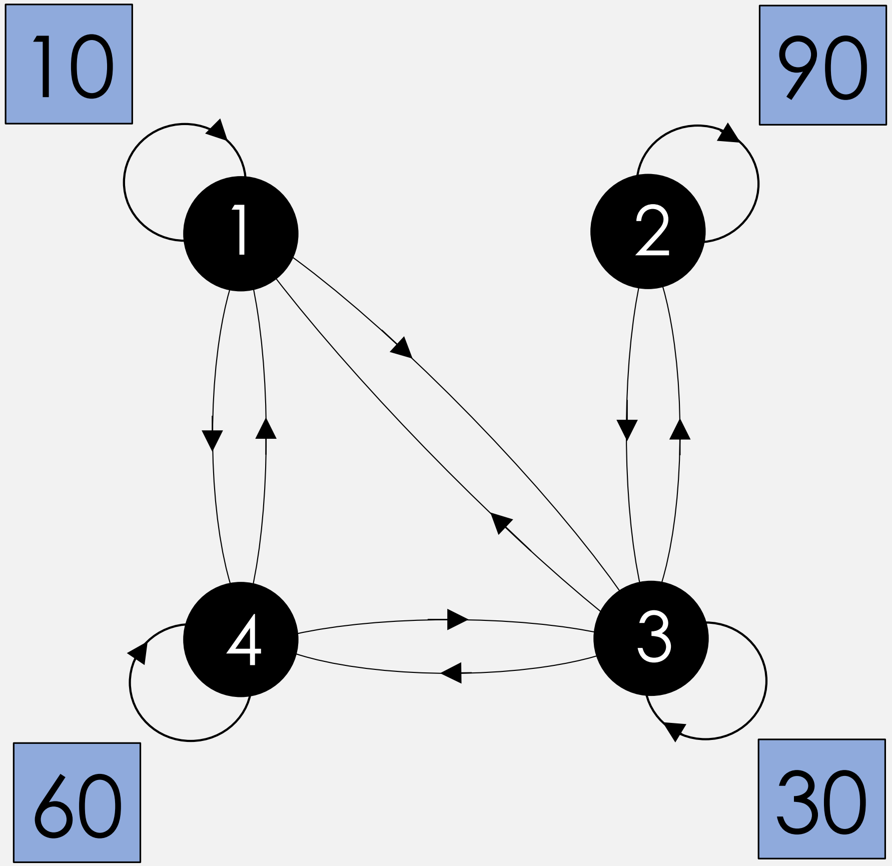
I am going to illustrate a method of opinion pooling on a network – this is the process and show you how we can produce consensus this way for problems where you have locational conflicts – so without more ado let me steam ahead and eventually come back at the end to primals and duals.


1
2
4
3
1
2
4
3

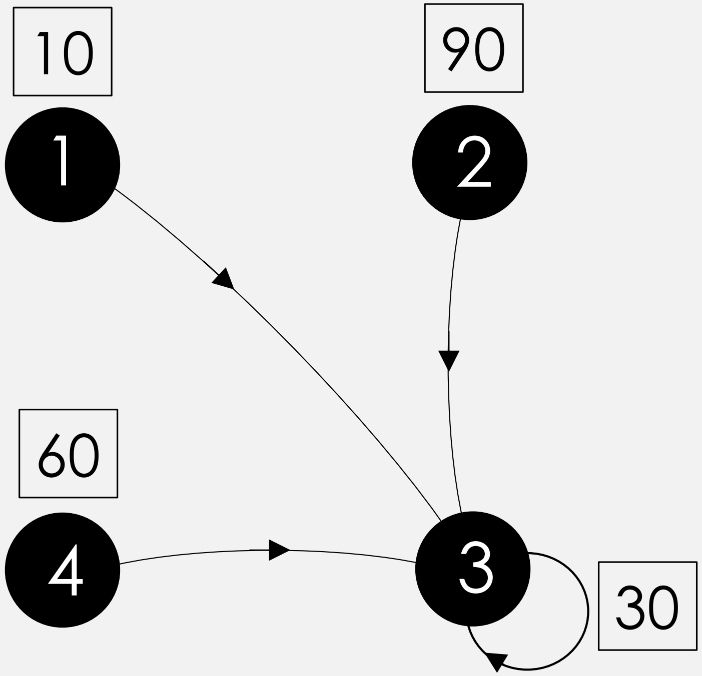
So this is our communications network where we can swap ideas – to some purpose such as pooling our opinions

Let us see how it works on a simple problem





We will give each actor in the network an opinion – here ***a number*** and then operate the network by asking them to communicate this number to their nearest neighbours – and then form ***a compromise*** – which is ***an average*** – a ***weighted*** average



This is how it works – we will illustrate it for actor 3 actor 1 communicates with 3 first then actor 2 then actor 4 does: and actor 3 then forms an 'average' of these 3 opinions with its own

(10 + 90 + 30 + 60) / 4 =
190/4 =..................47.5

(10+60+30)/3

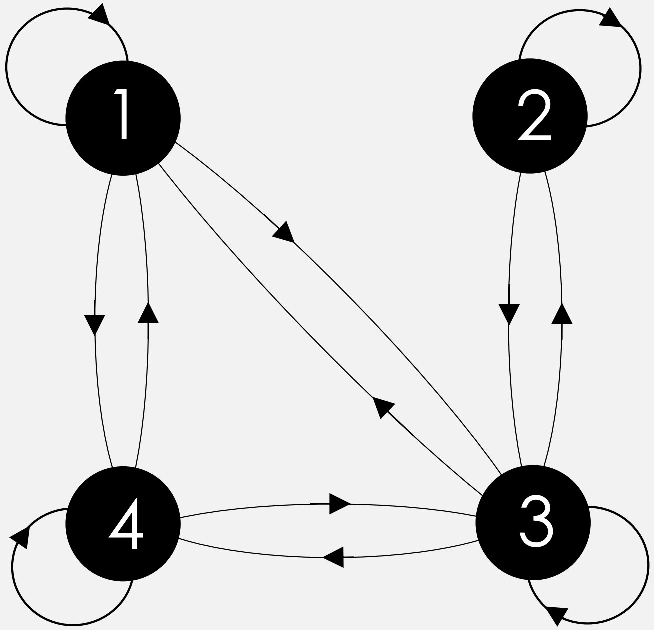
= 100/3

= 33.33

(90+30)/2

= 120/2

= 60



(60+10+30)/3

= 100/3

= 33.33

(30+90+10+60)/4

= 190/4

= 47.5

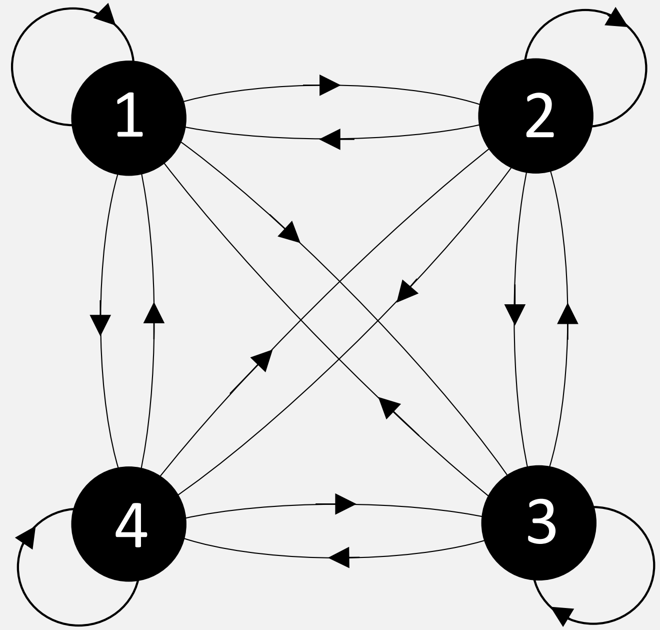
Now let us see what happens when we continue this process – already after the first pass, the weighted averaging reduces the difference between the numbers. If we continue this we get …

	Actor 1	Actor 2	Actor 3	Actor 4	
No of Actor	1.00	2.00	3.00	4.00	
Value-Number	10.00	90.00	60.00	30.00	
Digital	33.33	60.00	33.33	47.50	
2.00	38.06	53.75	38.06	43.54	
3.00	39.88	48.65	39.88	43.35	
4.00	41.04	46.00	41.04	42.94	
5.00	41.67	44.47	41.67	42.75	
6.00	42.03	43.61	42.03	42.64	
7.00	42.24	43.13	42.24	42.58	
8.00	42.35	42.85	42.35	42.55	
9.00	42.42	42.70	42.42	42.53	
10.00	42.45	42.61	42.45	42.51	

Let us see how it works on a simple problem

	Actor 1	Actor 2	Actor 3	Actor 4
No of Actor	**1.00**	**2.00**	**3.00**	**4.00**
Value-Number	**10.00**	**90.00**	**60.00**	**30.00**
1.00	33.33	60.00	33.33	47.50
2.00	38.06	53.75	38.06	43.54
3.00	39.88	48.65	39.88	43.35
4.00	41.04	46.00	41.04	42.94
5.00	41.67	44.47	41.67	42.75
6.00	42.03	43.61	42.03	42.64
7.00	42.24	43.13	42.24	42.58
8.00	42.35	42.85	42.35	42.55
9.00	42.42	42.70	42.42	42.53
10.00	**42.45**	**42.61**	**42.45**	**42.51**

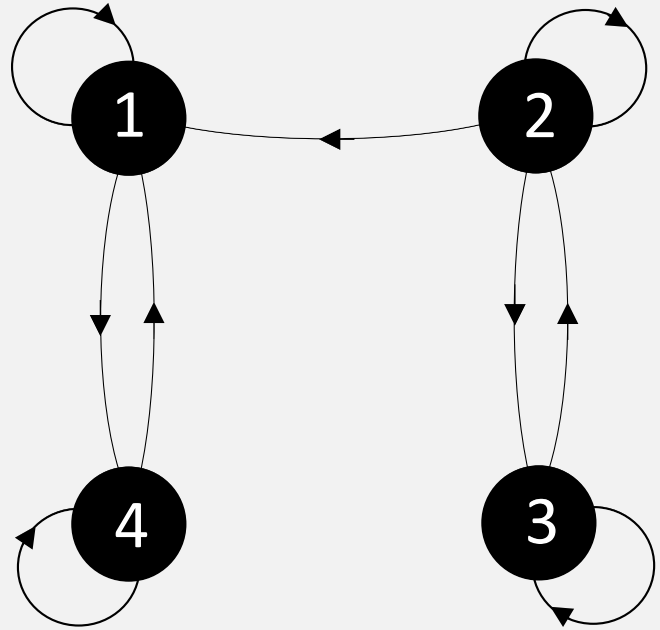
In fact if we have a network where everything is connected to everything else, we get immediate consensus – a network like this



If we have one that is disconnected we don't get convergence or consensus

In fact if we have a network where everything is connected to everything else, we get immediate consensus – a network like this

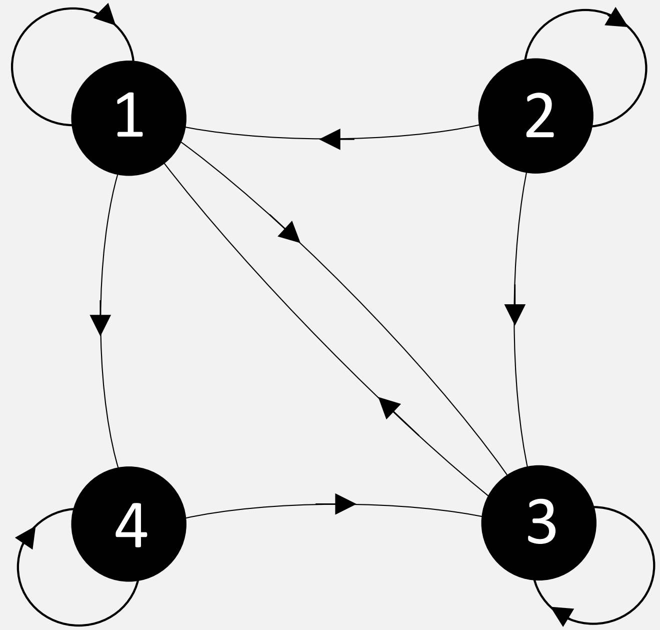
If we have one that is disconnected we don't get convergence or consensus



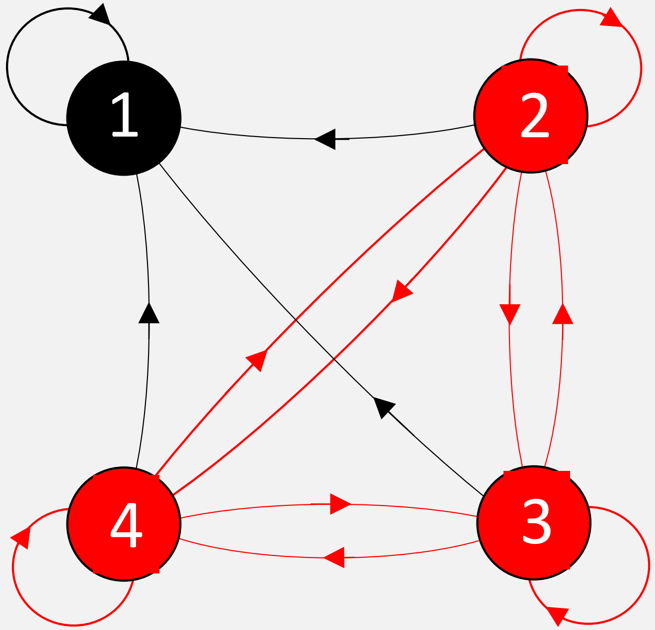
And we can have networks that imply that one actor dominates the final solution and so on and soon

We can have differential weights on the links as well as different topologies

Here actor 2 will dominate and the solution will be 90



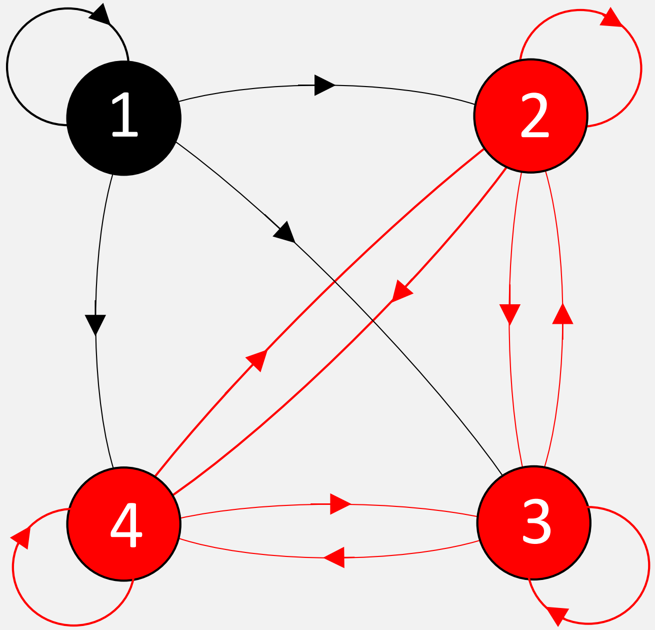
As a somewhat light-hearted interlude, we can use the graph to show some topical situations: what do you think this one is all about →



1 This is the UK for the last three years

2 3 4 This is the EU for the last three years

As a somewhat light-hearted interlude, we can use the graph to show some topical situations: what do you think this one is all about →



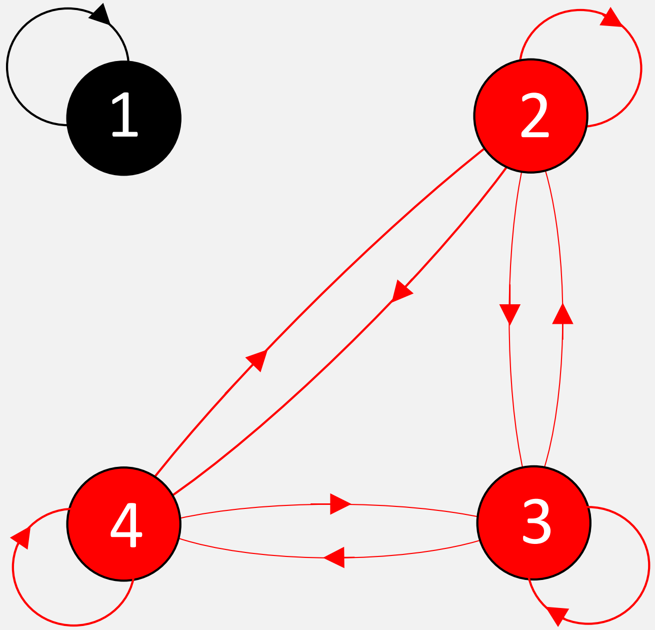
1 This is the UK today

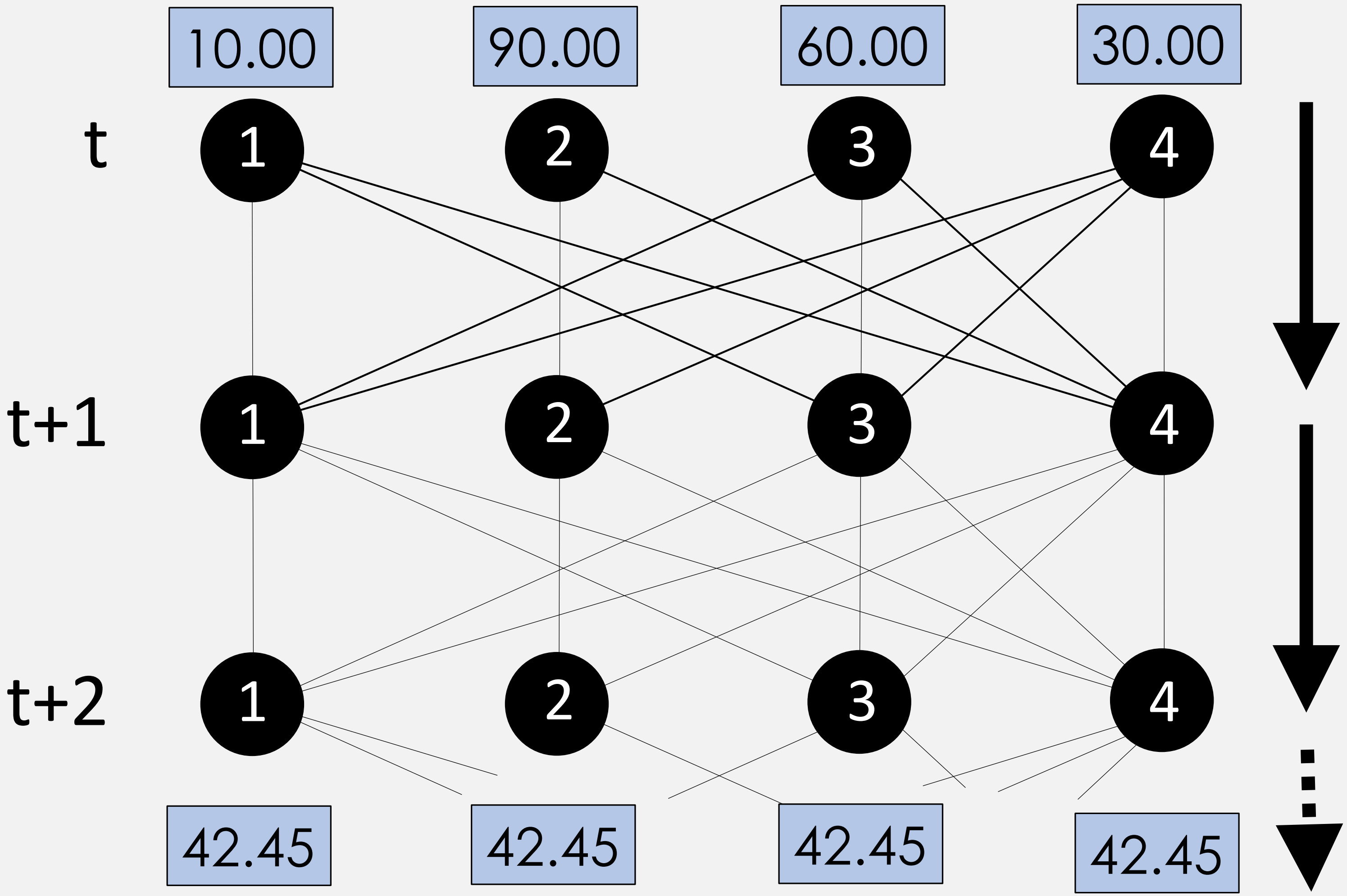
2 3 4 This is the EU now

And this is what it might be like this coming Saturday

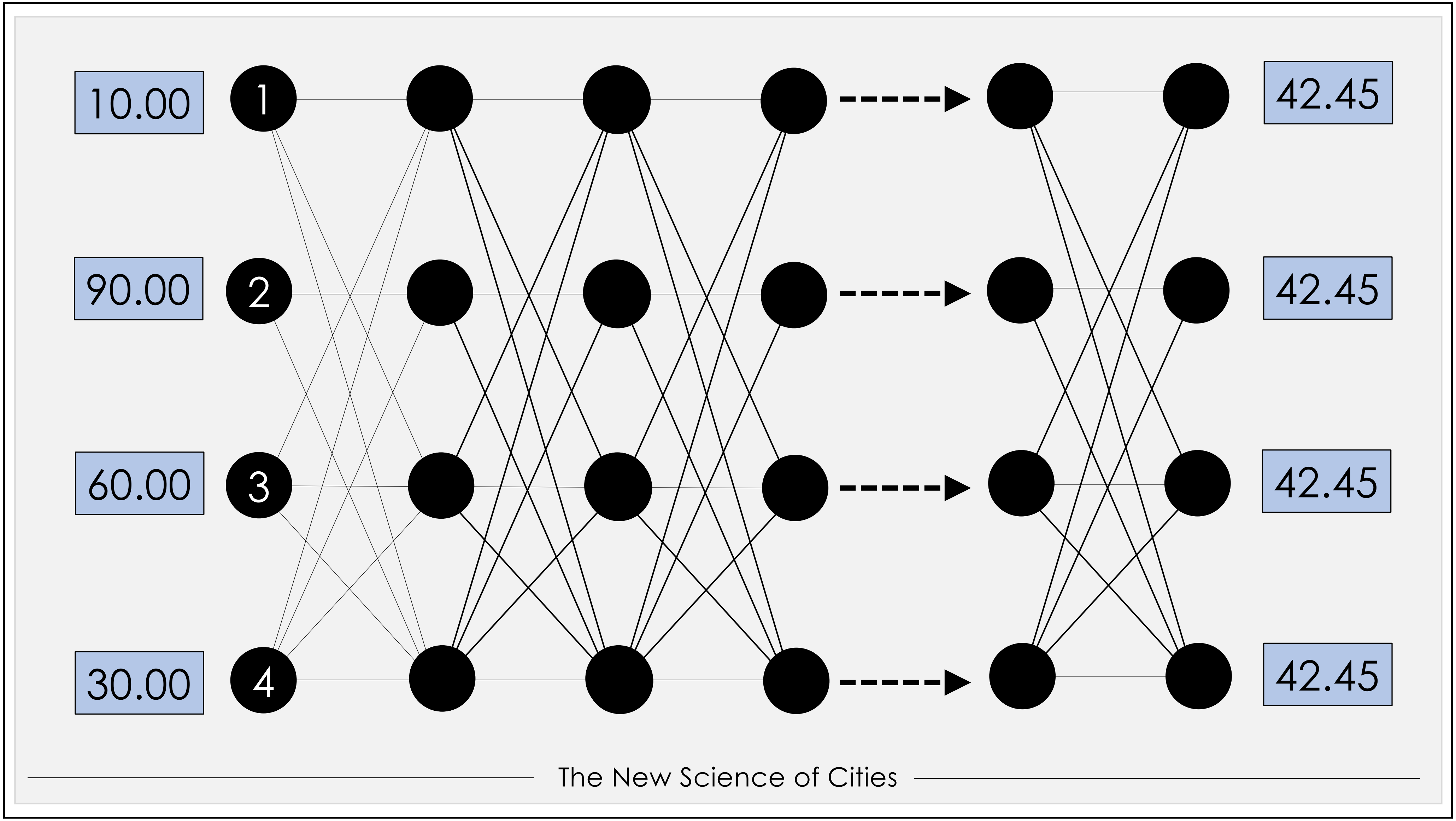
No deal !

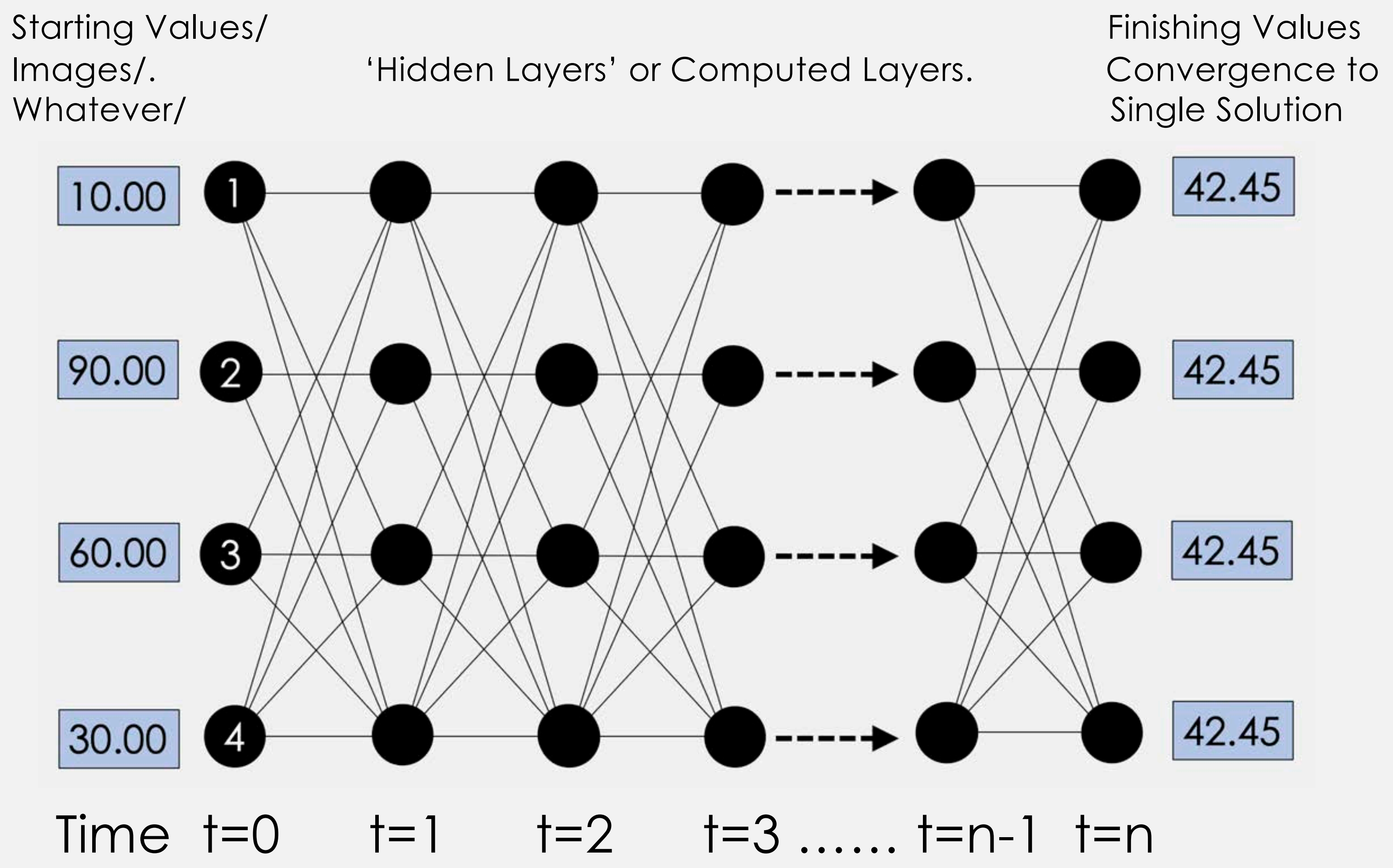
In fact it has lead to a **General Election** on December 15th this year which may well be the same thing





The New Science of Cities


10.00
90.00
60.00
30.00
1
2
3
4
42.45
42.45
42.45
42.45
The New Science of Cities

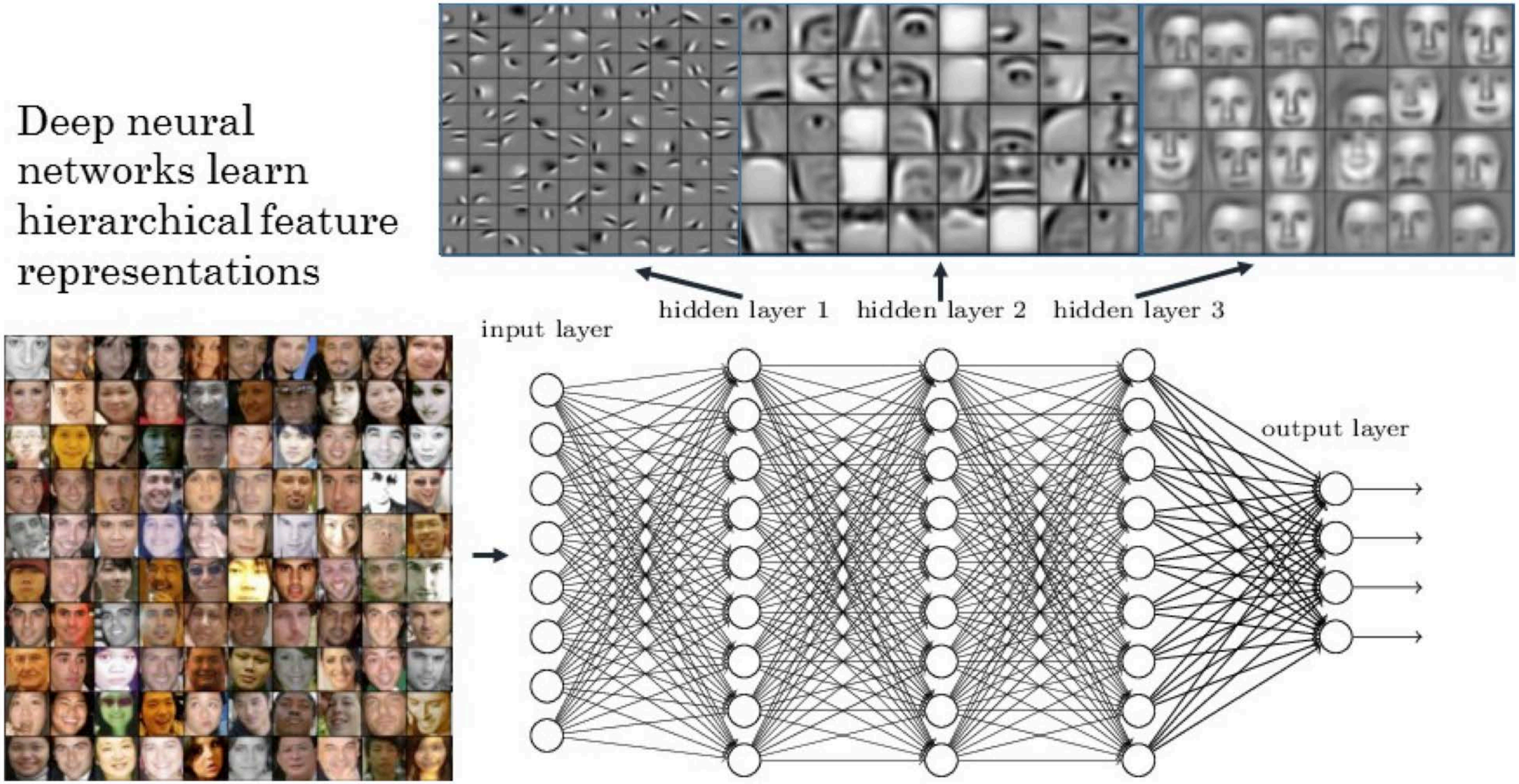

Starting Values/
Images/.
Whatever/
'Hidden Layers' or Computed Layers.
Finishing Values
Convergence to
Single Solution
10.00
90.00
60.00
30.00
1
2
3
4
42.45
42.45
42.45
42.45
Time t=0 t=1 t=2 t=3 …… t=n-1 t=n

So what does this remind you of

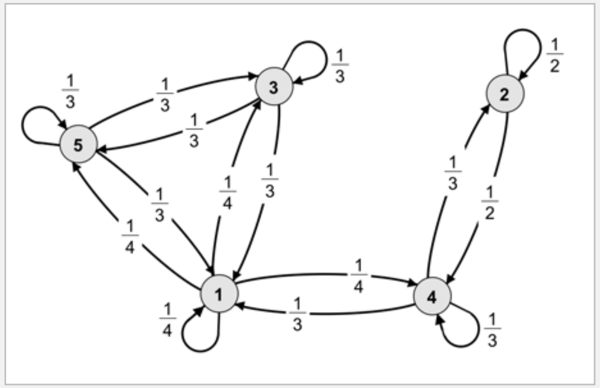
Yes, Neural Nets, the darling of machine learning !....

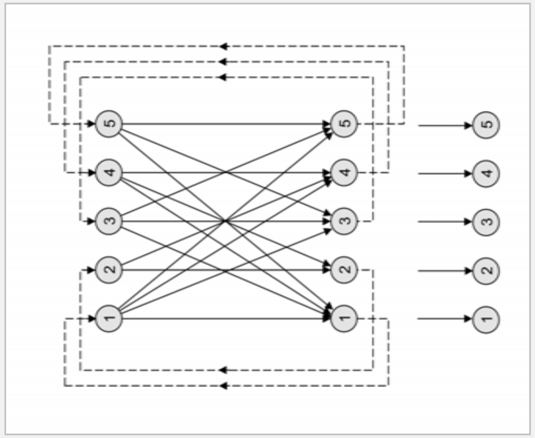
Here we are not bombarding our senses with images so that we can extract patterns for recognition but we are converging on a solution in the same way. But this doesn't imply learning. It could do if we altered the weights though – the layer is just repeated until convergence

Deep neural networks learn hierarchical feature representations



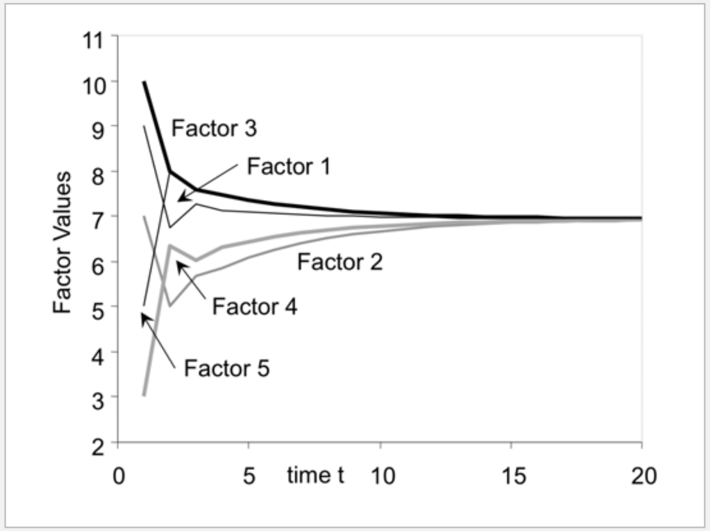
A Summary So Far: The Network, The Averaging Process, the Machine, the Algebra





$$
\begin{bmatrix} 1 & 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \end{bmatrix}
\quad
\begin{bmatrix} 1/4 & 0 & 1/4 & 1/4 & 1/4 \\ 0 & 1/2 & 0 & 1/2 & 0 \\ 1/3 & 0 & 1/3 & 0 & 1/3 \\ 1/3 & 1/3 & 0 & 1/3 & 0 \\ 1/3 & 0 & 1/3 & 0 & 1/3 \end{bmatrix}
$$

$$a_i(t+1) = \sum_{j=1}^{n} W_{ij} a_j(t)$$

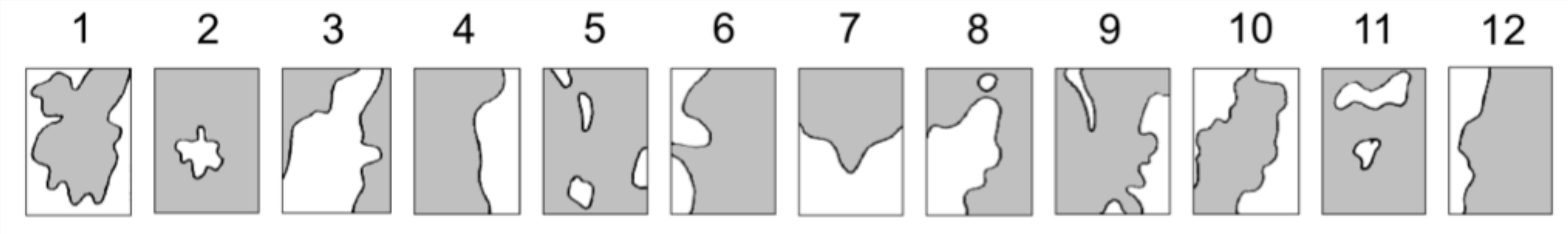


$$a_i(t+1) = b_i(t) + \sum_{j=1}^{n} W_{ij} a_j(t)$$

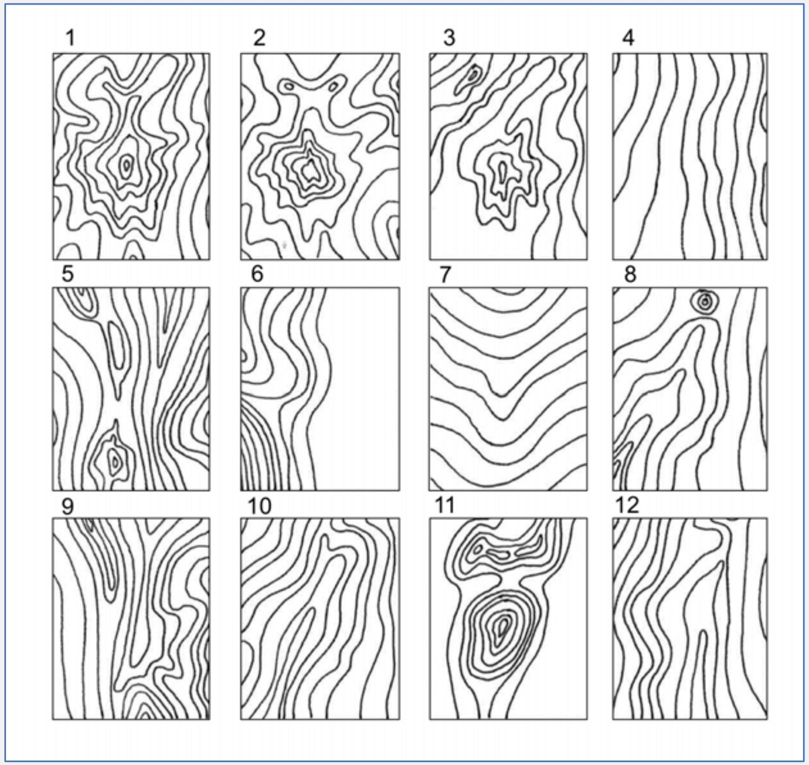
Spatial Averaging: An Example

- A set of factors showing the desirability of land development –our opinions expressed as maps
- These conflict with one another
- We form a network showing the strongest conflicts – any measure of similarity/dissimilarity
- We make sure the network is connected as this implies the weights
- We perform the averaging

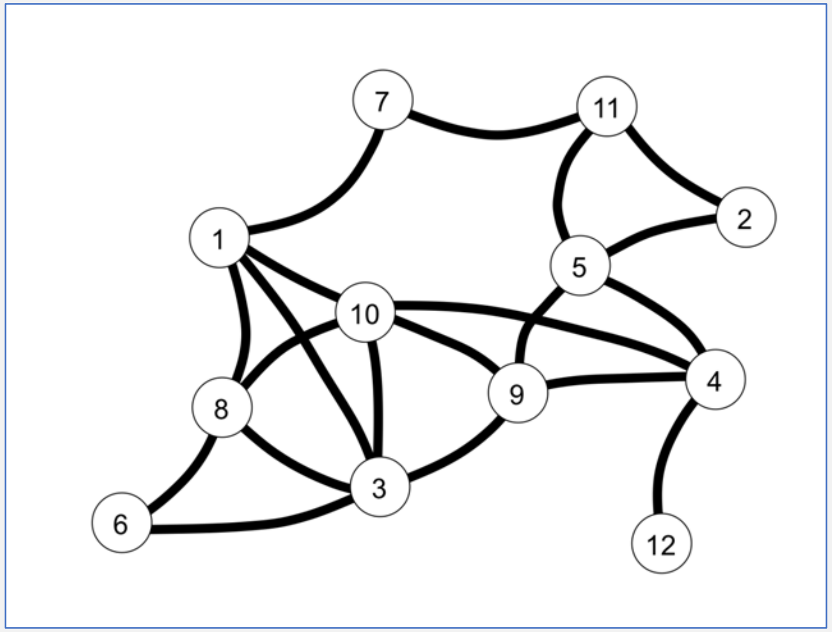
Key Factors Affecting Residential Development

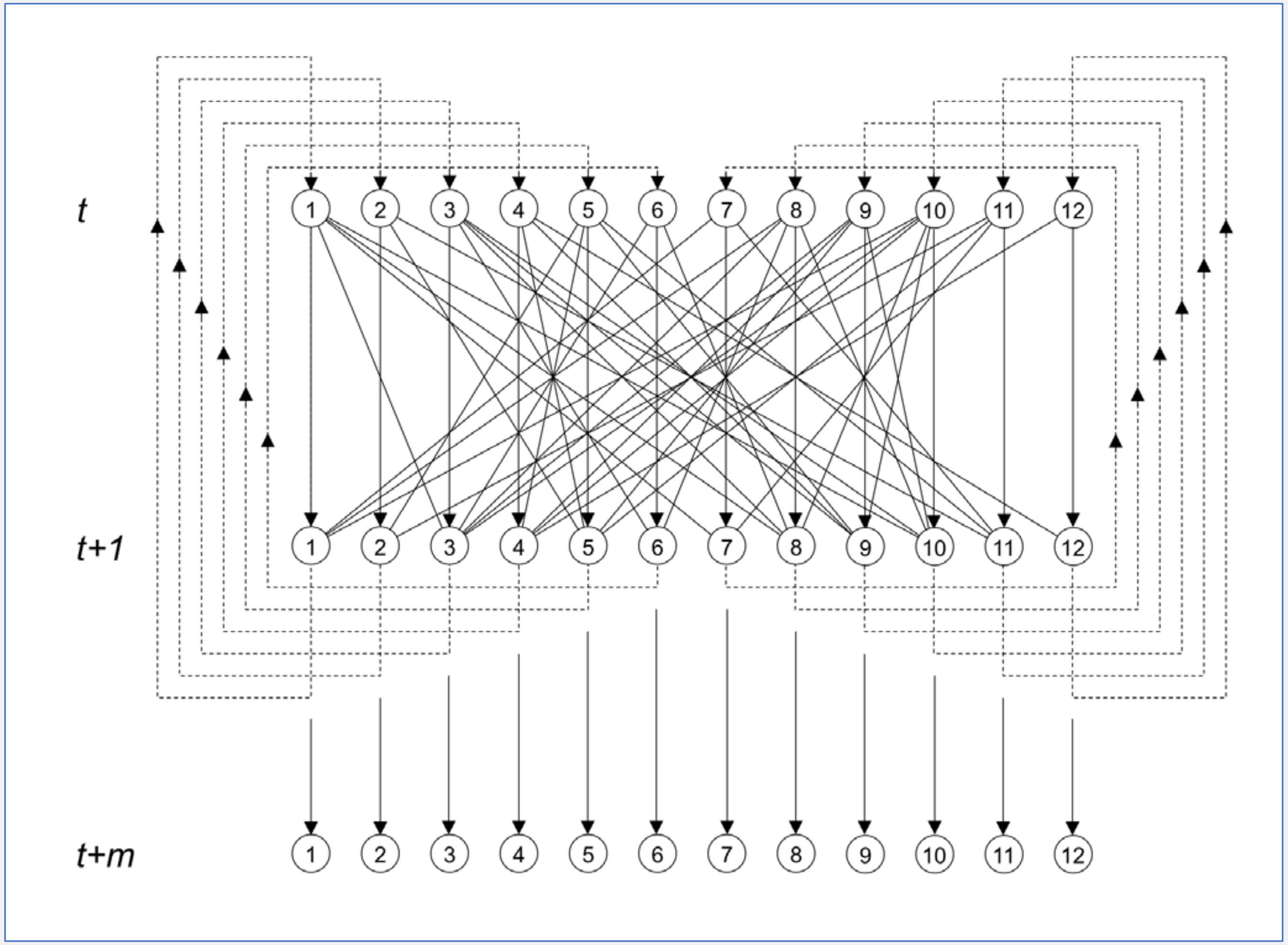


1. Accessibility to Existing Urban Services
2. Costs of Spatial Congestion
3. Accessibility to Recreational Amenities
4. Areas of Acceptable Micro-Climate
5. Areas of Water Catchment and Poor Drainage
6. Institutional Constraints Imposed by Government
7. Accessibility to External Urban Markets
8. Subsidence and Extensive Industrial Pollution
9. Areas of Suitable Topography
10. Rural Amenity Areas
11. Historic Urban Areas
12. Conservation of High Quality Agricultural Quality



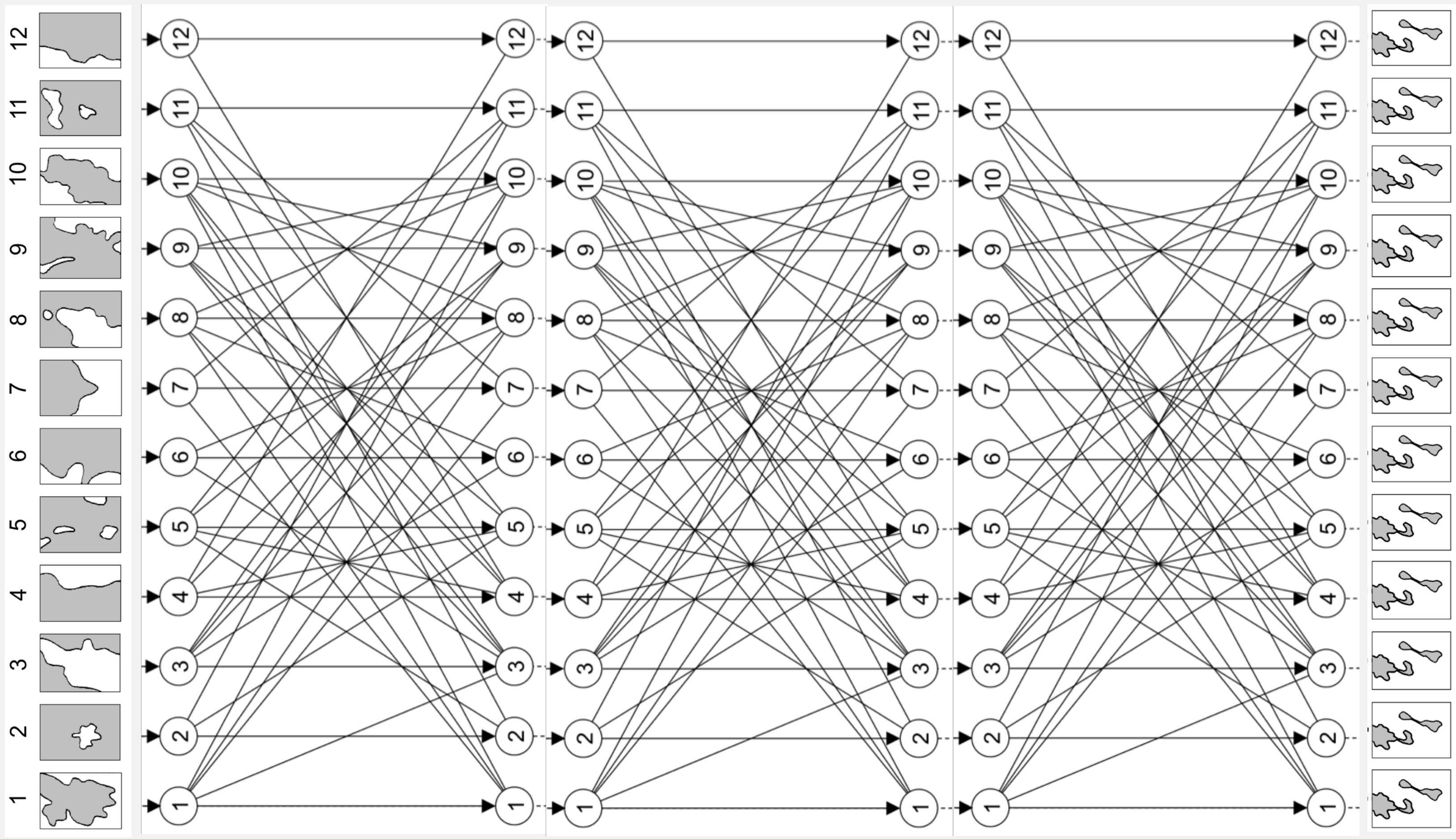
Turn the maps into contours of desirability or suitability




t
t+1
t+m
1
2
3
4
5
6
7
8
9
10
11
12

Key Factors Affecting Residential Development

- Accessibility to Existing Urban Services
- Costs of Spatial Congestion
- Accessibility to Recreational Amenities
- Areas of Acceptable Micro-Climate
- Areas of Water Catchment and Poor Drainage
- Institutional Constraints Imposed by Government
- Accessibility to External Urban Markets
- Subsidence and Extensive Industrial Pollution
- Areas of Suitable Topography
- Rural Amenity Areas
- Historic Urban Areas
- Conservation of High Quality Agricultural Quality

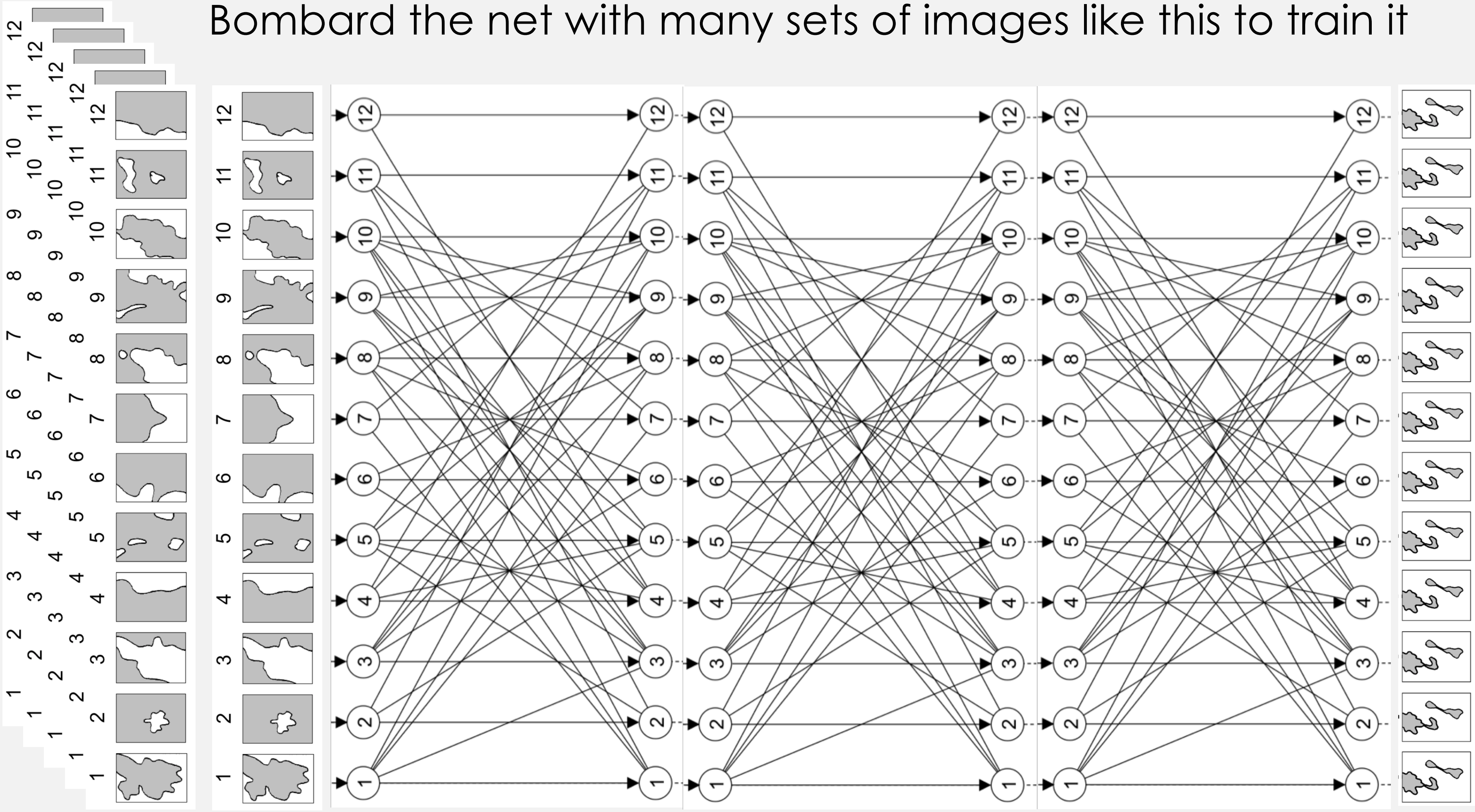

12
11
10
9
8
7
6
5
4
3
2
1

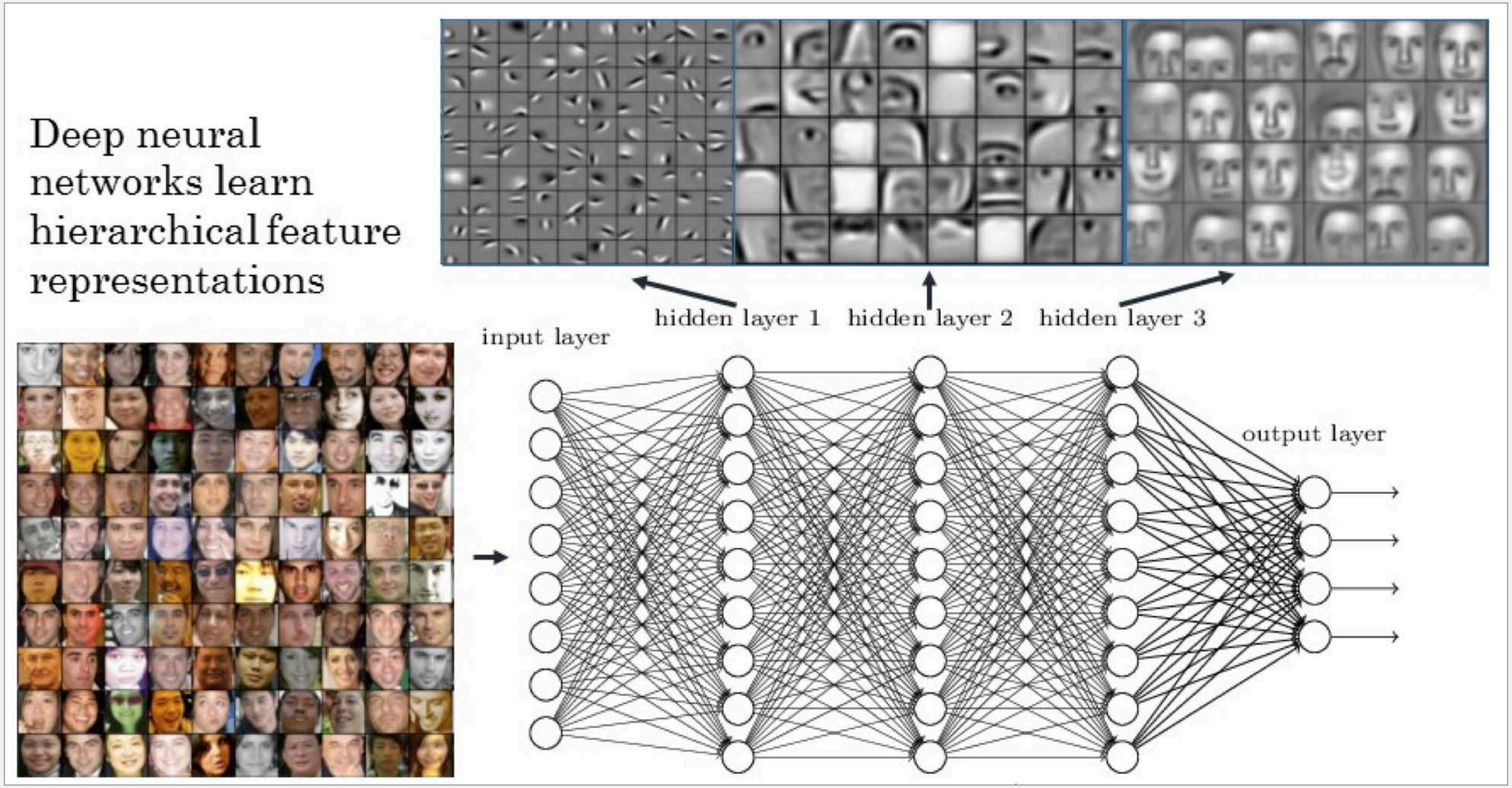
- Imagine there were only 12 factors that determined urban development, things like accessibility, topography etc..

- If we had many, many towns and relevant sets of 12 factors for each, these factors are images, and we could throw them at our neural net and we could train the net to produce a unique set of weights that would produce the most relevant combination of factors that would determine the most likely town form.

- This is a great challenge. I wonder if there is a student out there on the MSc course who might like to have a go at doing this sort of thing for a dissertation next year

Bombard the net with many sets of images like this to train it




Deep neural networks learn hierarchical feature representations
hidden layer 1
hidden layer 2
hidden layer 3
input layer
output layer

A More Elaborate Construction

- Now we first construct a network.
- Each map is coded on some desirability/utility scale –the simplest is 0 cannot be developed – 1 can be developed
- The maps conflict – represent the map as a vector

1	0	1
0	0	1
0	1	0

$$\longrightarrow \quad [\,1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0\,]$$

Actors/
Agents

Locations →

1	1	0	1	0	0	1	0	1
2	0	0	0	1	0	0	0	1
3	0	0	1	0	0	1	0	1
n	•	•	•	•	•	•	•	•

= Matrix [M]

Note that I have dropped one cell in the map because my last example relates to 8 locations, not 9

The interactions between the agents can be seen in terms of the maps in the time-honoured way using the convention of forming the similarity or covariance

$$\begin{bmatrix} 3 & 1 & 3 & 3 & 3 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 \\ 3 & 1 & 3 & 3 & 3 & 1 \\ 3 & 1 & 3 & 5 & 4 & 2 \\ 3 & 1 & 3 & 4 & 7 & 2 \\ 1 & 0 & 1 & 2 & 2 & 2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

$$A \quad = \quad M \quad M^T$$

The Map for Actor 1

Now this is looking at links between agents through the maps – we can also look at links through the agents. The first problem we call the **primal**, the second the **dual**

$$
\begin{bmatrix}
1&1&1&1&1&1&0&1\\
1&1&1&1&1&1&0&1\\
1&1&4&1&2&4&1&4\\
1&1&1&1&1&1&0&1\\
1&1&2&1&3&3&1&2\\
1&0&4&1&3&5&1&4\\
0&0&1&0&1&1&1&1\\
1&1&4&1&2&4&1&5
\end{bmatrix}
=
\begin{bmatrix}
0&0&0&0&1&0\\
0&0&0&0&1&0\\
1&0&1&1&1&0\\
0&0&0&0&1&0\\
0&0&0&1&1&1\\
1&0&1&1&1&1\\
0&0&0&1&0&0\\
1&1&1&1&1&0
\end{bmatrix}
\begin{bmatrix}
0&0&1&0&0&1&0&1\\
0&0&0&0&0&0&0&1\\
0&0&1&0&0&1&0&1\\
0&0&1&0&1&1&1&1\\
1&1&1&1&1&1&0&1\\
0&0&0&0&1&1&0&0
\end{bmatrix}
$$

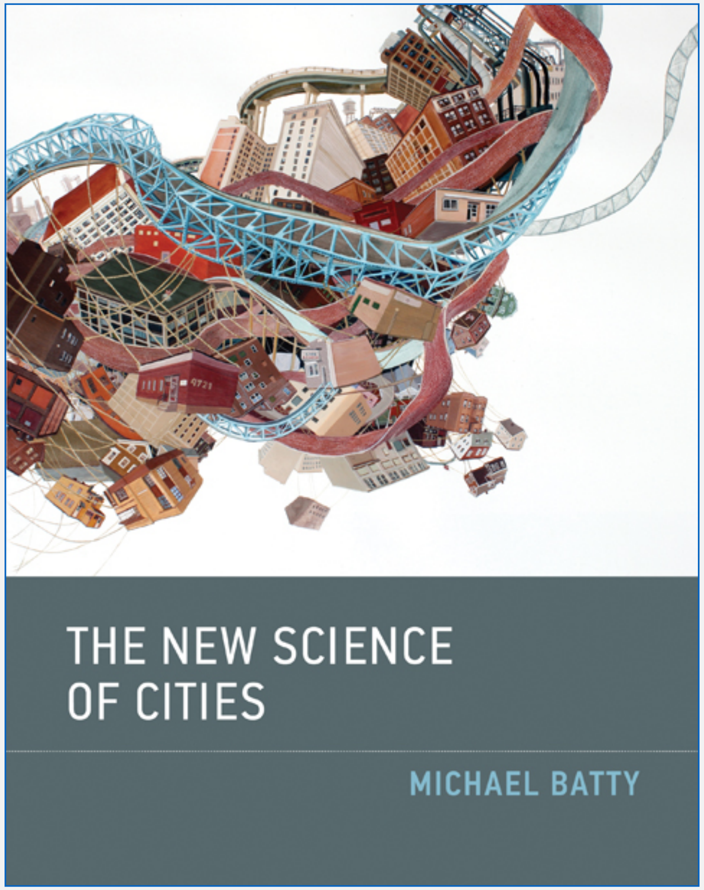
$$S = M^T \; M$$

Now there is quite a lot of algebra of these processes – if we consider the primal, the spatial averaging is a Markov chain – regular and connected and strong in the terminology

If we consider the averaging over agents for each site 0 - the dual, this is also a Markov chain but a dual.

In fact I have written an entire book on this – or at least the third part of the book which no one ever reads is all about this. This is my ***The New Science of Cities*** book

And my first paper on this was written when …….



References over Many Years

French, J. R. P. (1956) A Formal Theory of Social Power, **Psychological Review**, **63**, 181-194.

Batty, M. (1971) An Approach to Rational Design: 1: The Structure of Design Problems, 2: Design Problems as Markov Chains, **Architectural Design**, **41**, 436-9, 498-501

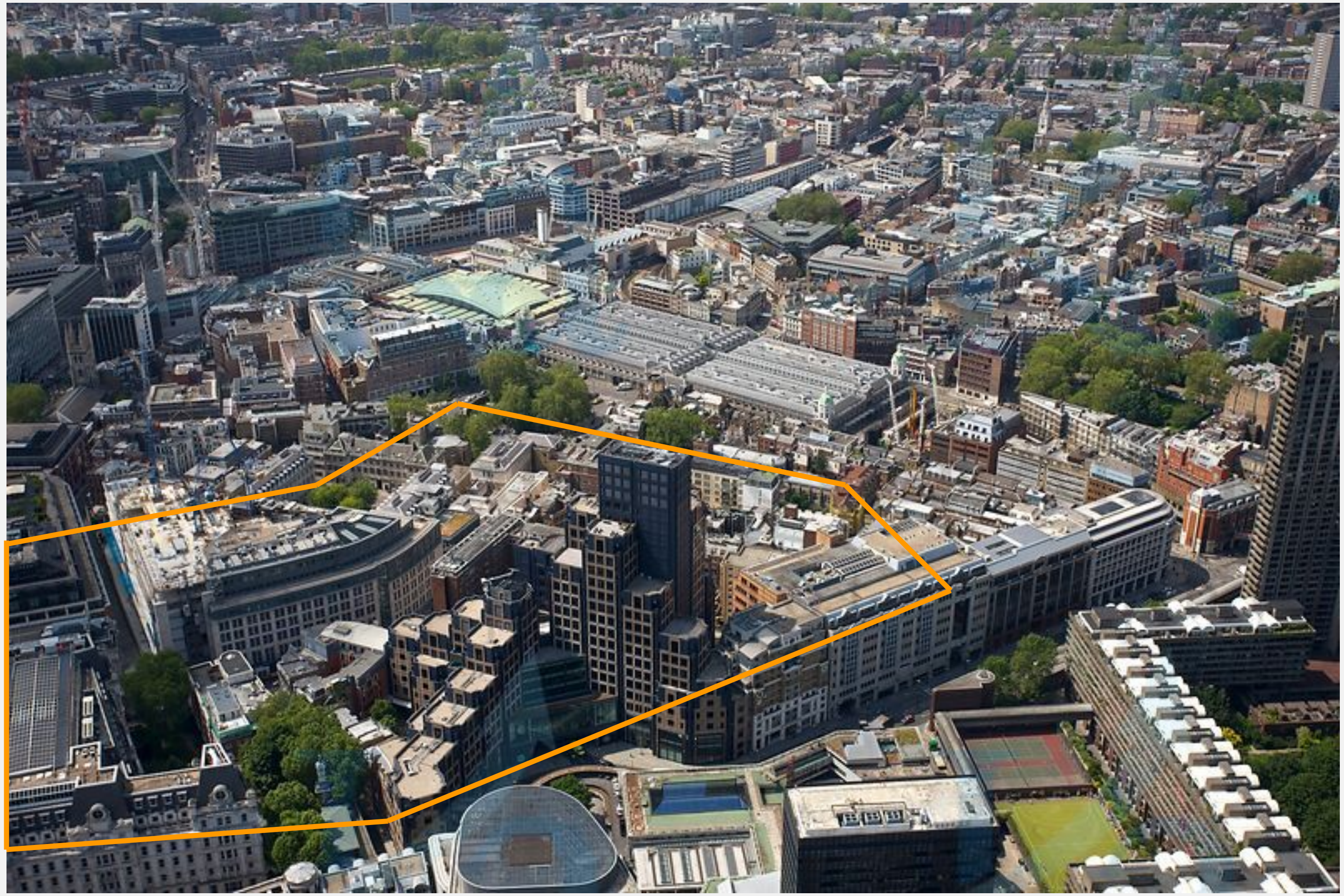
Batty, M. (1984) Plan Design and Committee Decision-Making, **Environment and Planning B**, **11**, 279-295.

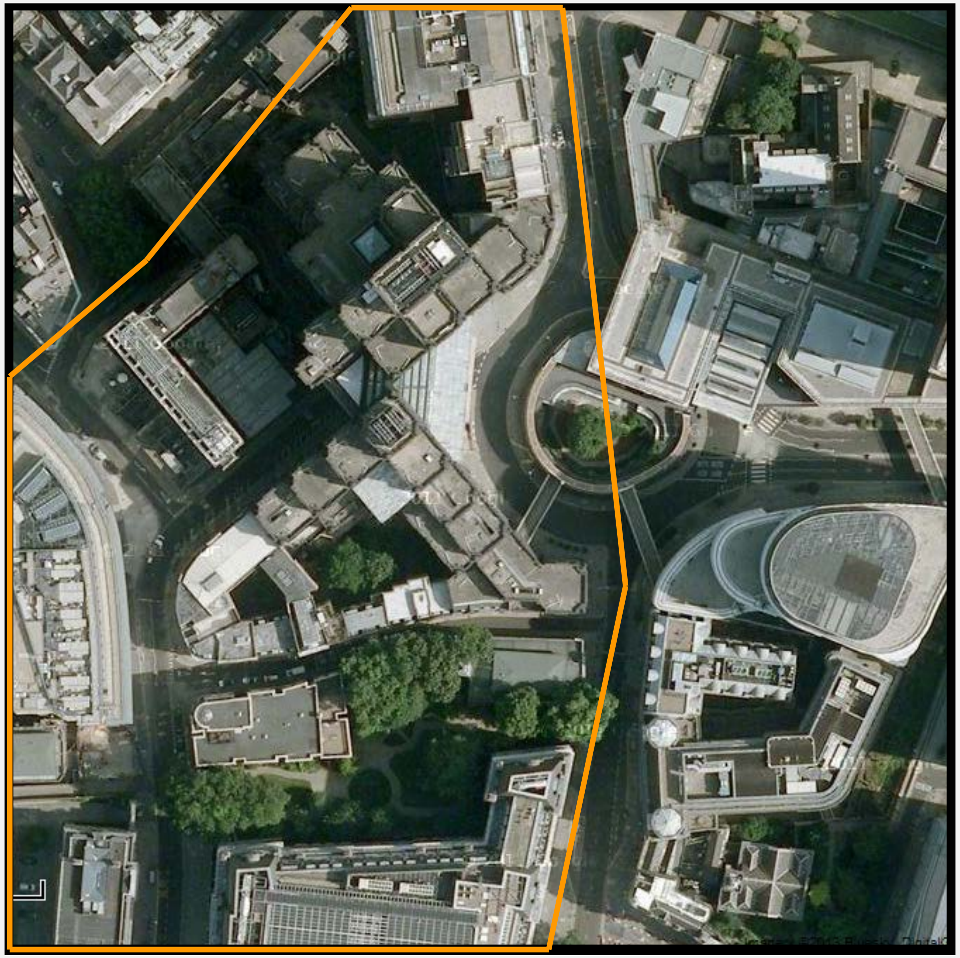
Blondel, V. D., et al. (2005) Convergence in Multiagent Coordination, Consensus, and Flocking, In **Proc Joint 44th IEEE Conference on Decision and Control**, Seville, Spain, December 12-15, 2005,

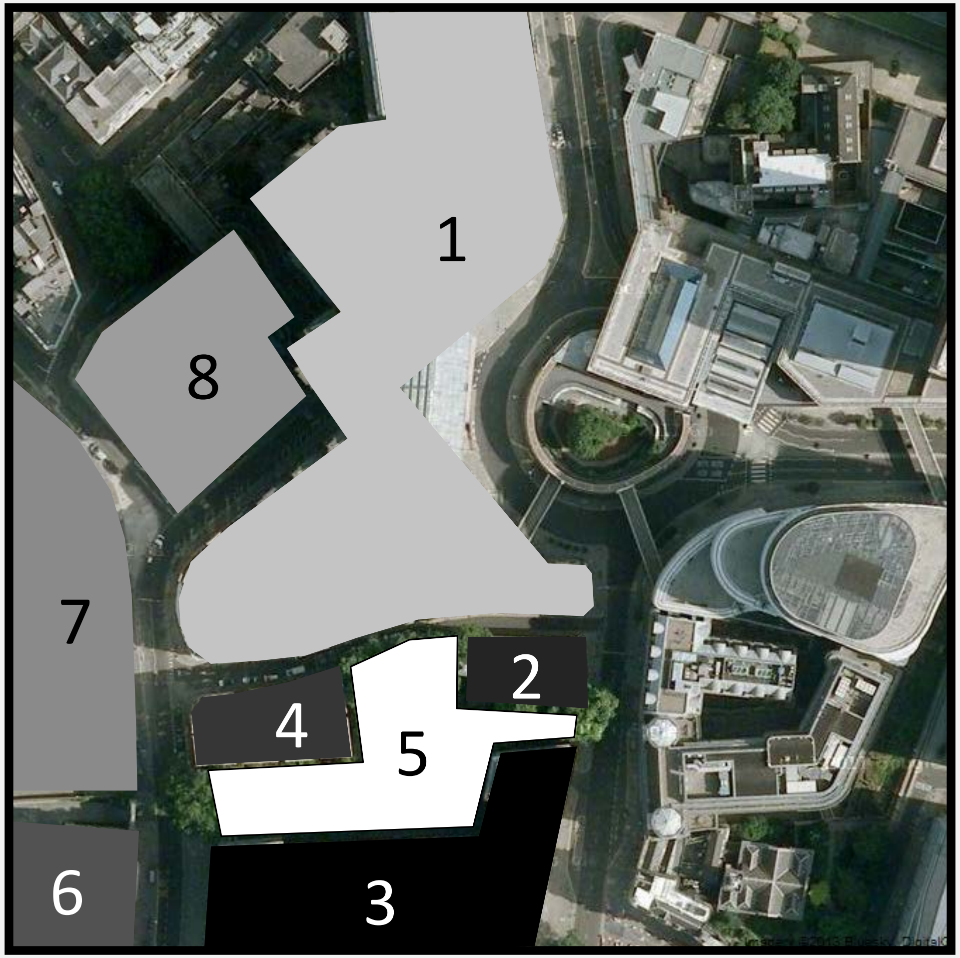
Batty, M. (2013) **The New Science of Cities**, MIT Press, Cambridge, MA.

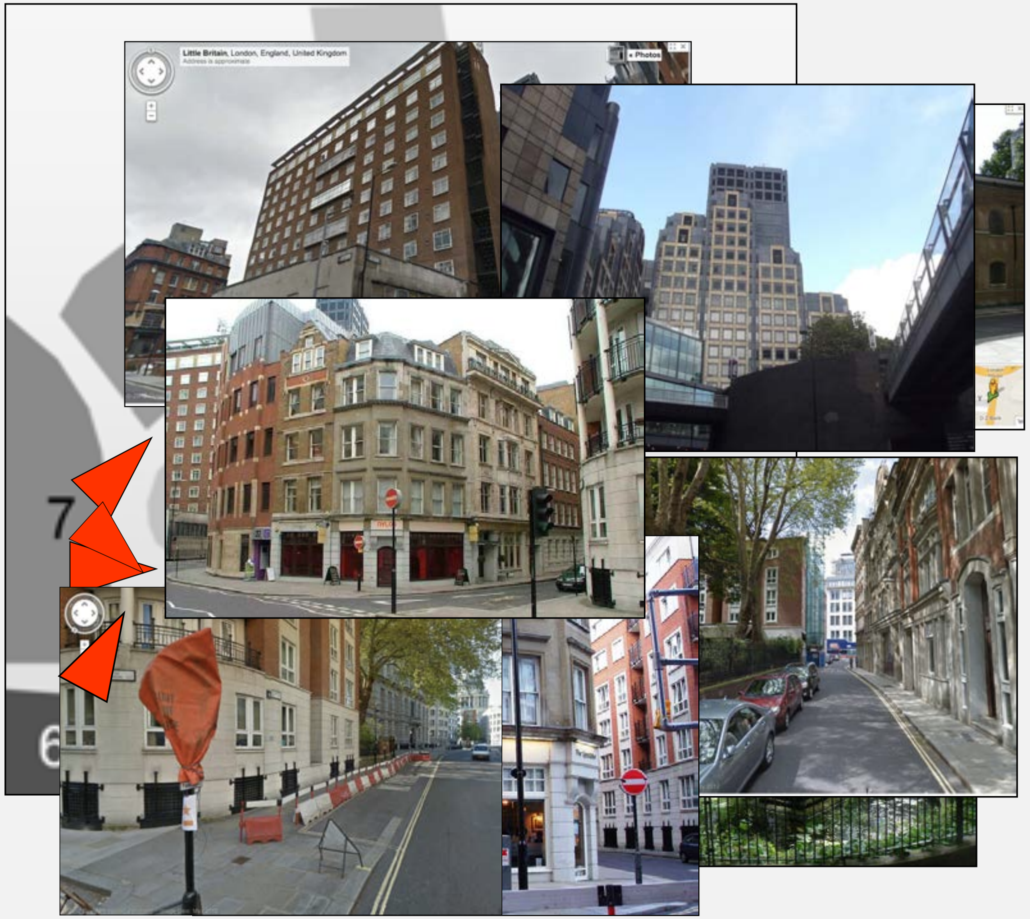
Gulzar, M. M. et al. (2018) Multi-Agent Cooperative Control Consensus: A Comparative Review, **Electronics**, **7**, 1-20

- Now I could finish here and not outstay my welcome but let me introduce one last example to show where this is going. This is a problem of development in the City of London – in the financial quarter where there is intense pressure to develop but intense control of the environment
- In fact it is so controlled that there are police cameras everywhere and a cordon around the City and no on-street parking and so on
- My example involves a small area near St. Paul’s cathedral where there are 6 key actors and 8 sites.
- We want to figure the power of these actors in the problem






1
8
7
2
4
5
6
3



The New Science of Cities

Actors/Stakeholders

1 City Corporation

2 Residents

3 Hospital NHS

4 Developers

5 Property Speculators

6 Banks

Sites/Buildings/Locations

1 Aldersgate Complex

2 St Botolph's

3 Nomura House

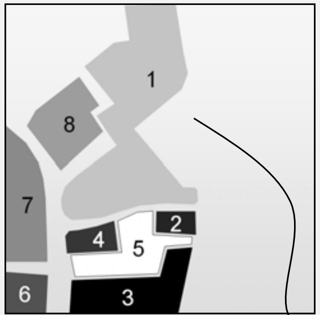
4 Milton House

5 Postman's' Park

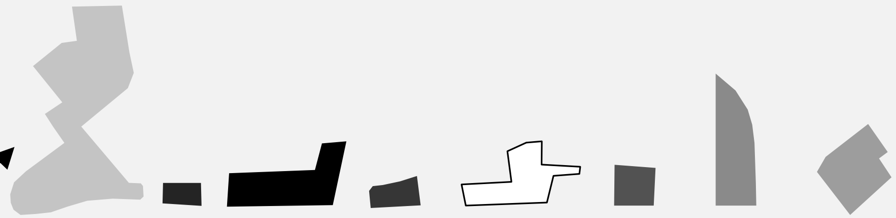
6 Bank of America

7 Barts New Building

8 Barts Old Building



Sites/Buildings



Agents

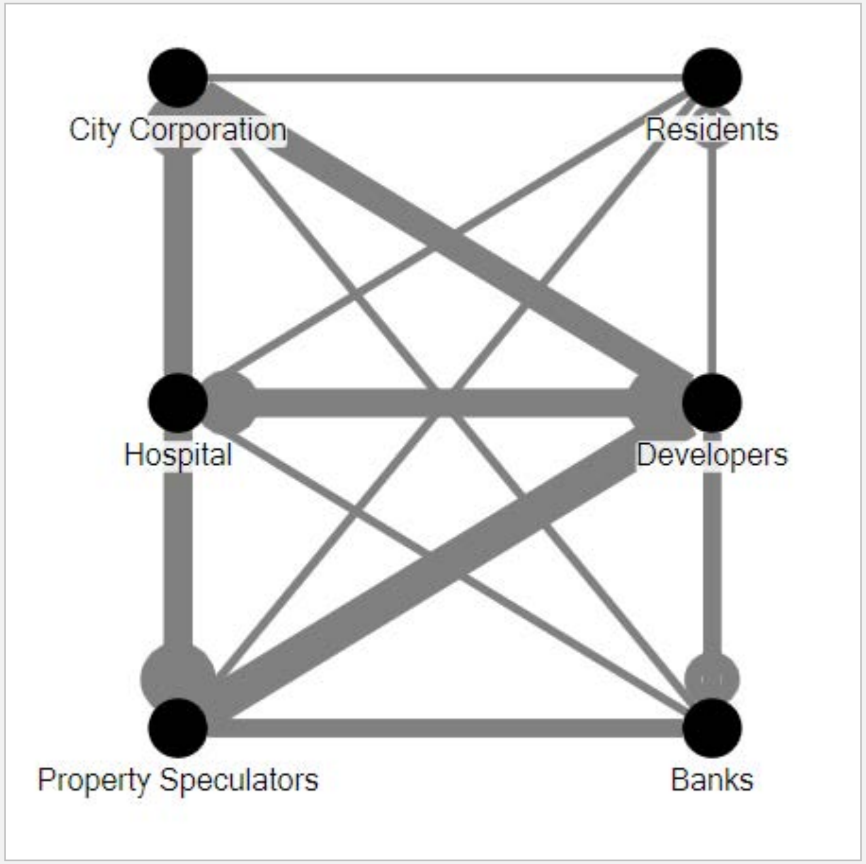
Agents	1	2	3	4	5	6	7	8
1 City Corporation	0	0	1	0	0	1	0	1
2 Residents	0	0	0	0	0	0	0	1
3 Hospital NHS	0	0	1	0	0	1	0	1
4 Developers 5 Property Speculators 6 Banks	●	●	●	●	●	●	●	●

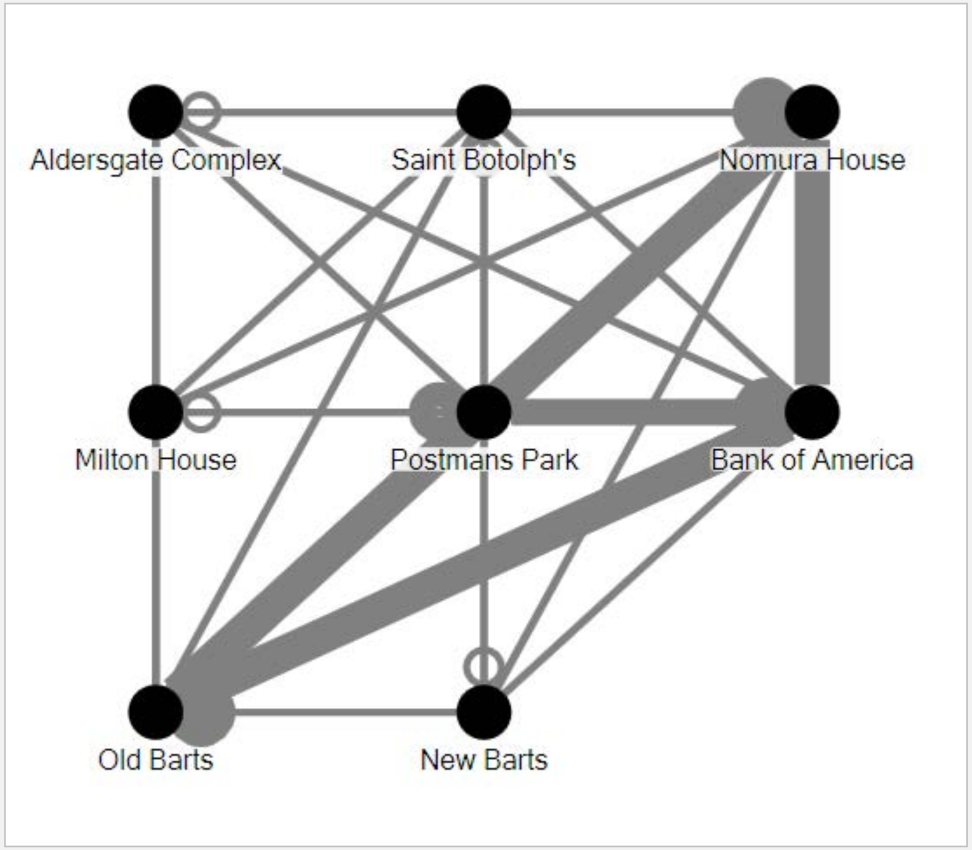
Sites/Buildings

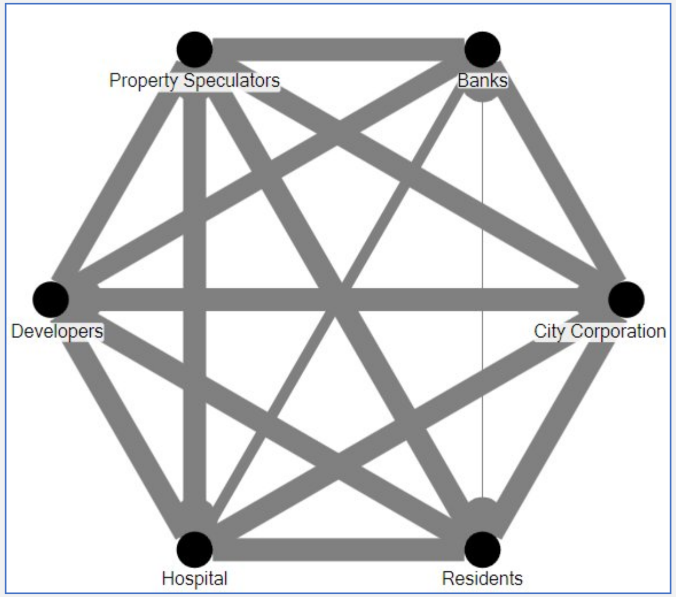
1 Aldersgate Complex
2 St Botolph’s
3 Nomura House
4 Milton House
5 Postman's’ Park
6 Bank of America
7 Barts New Building
8 Barts Old Building

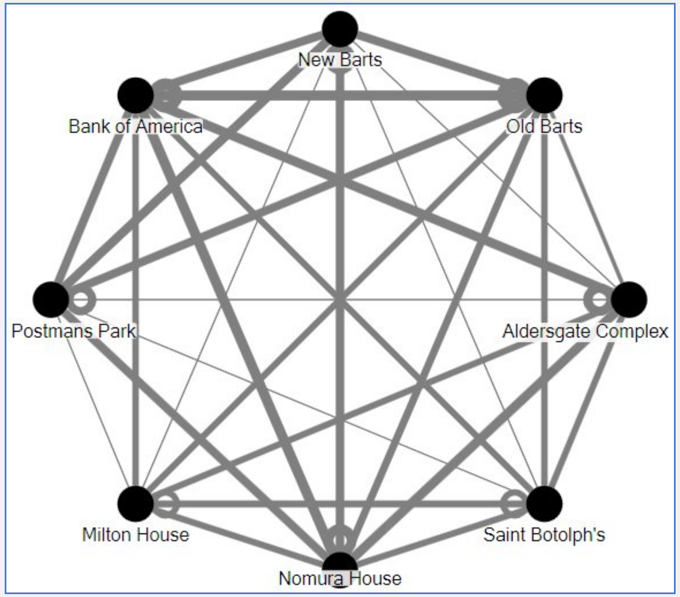
Agents

$$
\begin{array}{l}
\text{1 City Corporation} \\
\text{2 Residents} \\
\text{3 Hospital NHS} \\
\text{4 Developers} \\
\text{5 Property Spec} \\
\text{6 Banks}
\end{array}
\begin{bmatrix}
0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0
\end{bmatrix}
= M
$$


City Corporation
Residents
Hospital
Developers
Property Speculators
Banks


Aldersgate Complex
Saint Botolph's
Nomura House
Milton House
Postmans Park
Bank of America
Old Barts
New Barts


Property Speculators
Banks
Developers
City Corporation
Hospital
Residents


New Barts
Bank of America
Old Barts
Postmans Park
Aldersgate Complex
Milton House
Saint Botolph's
Nomura House

The Network Averaging X Set of Maps

$$\begin{bmatrix} 3/14 & 1/14 & 3/14 & 3/14 & 3/14 & 1/14 \\ 1/5 & 1/5 & 1/5 & 1/5 & 1/5 & 0 \\ 3/14 & 1/14 & 3/14 & 3/14 & 3/14 & 1/14 \\ 3/18 & 1/18 & 3/18 & 5/18 & 4/18 & 2/18 \\ 3/20 & 1/20 & 3/10 & 4/20 & 7/20 & 2/20 \\ 1/8 & 0 & 1/8 & 2/8 & 2/8 & 2/8 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \end{bmatrix}$$

yields

A New Averaged Set of Maps

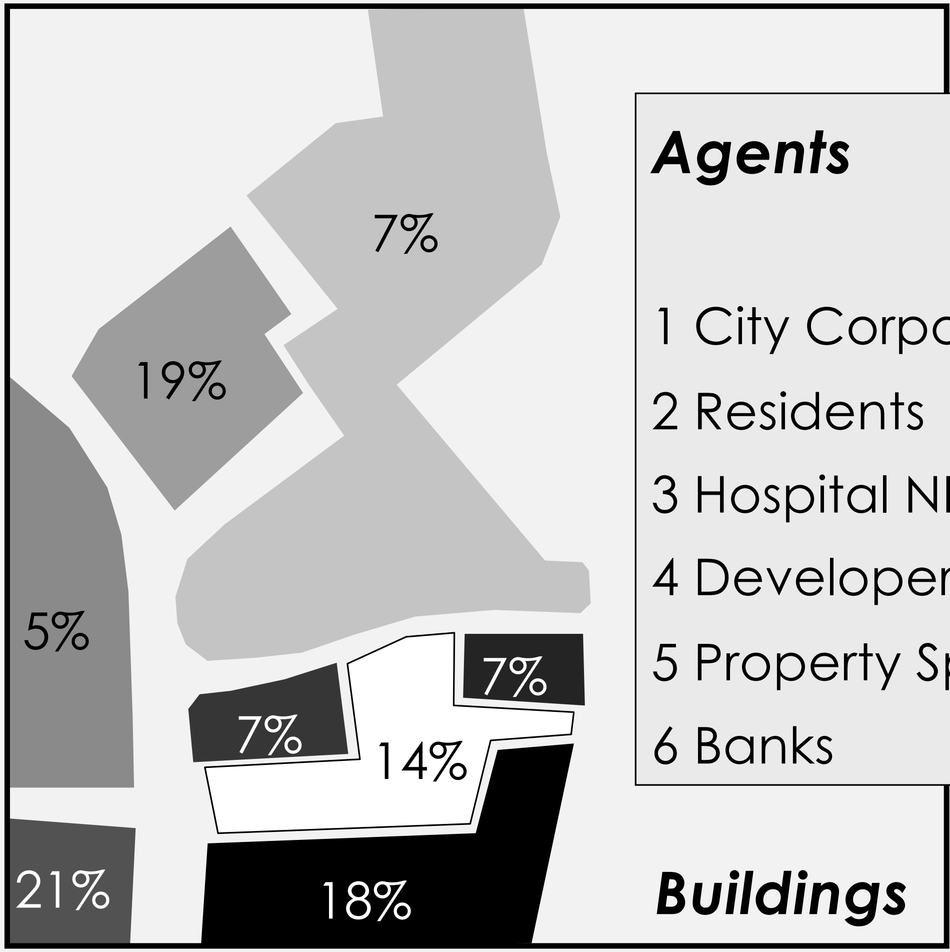
$$\begin{bmatrix} 0.21 & 0.21 & 0.86 & 0.21 & 0.50 & 0.93 \\ 0.20 & 0.20 & 0.80 & 0.20 & 0.40 & 0.80 \\ 0.21 & 0.21 & 0.86 & 0.21 & 0.50 & 0.93 \\ 0.22 & 0.22 & 0.83 & 0.22 & 0.61 & 0.94 \\ 0.35 & 0.35 & 0.85 & 0.35 & 0.65 & 0.95 \\ 0.25 & 0.25 & 0.75 & 0.25 & 0.75 & 1.00 \end{bmatrix}$$

And then we average them again using the same network
And this yields a new map, And so on until all the differences between the actors with respect to their maps are ironed out and we get the following map

$$\begin{bmatrix} 0.25 & 0.25 & 0.84 & 0.25 & 0.58 & 0.94 \\ 0.25 & 0.25 & 0.84 & 0.25 & 0.58 & 0.94 \\ 0.25 & 0.25 & 0.84 & 0.25 & 0.58 & 0.94 \\ 0.25 & 0.25 & 0.84 & 0.25 & 0.58 & 0.94 \\ 0.25 & 0.25 & 0.84 & 0.25 & 0.58 & 0.94 \\ 0.25 & 0.25 & 0.84 & 0.25 & 0.58 & 0.94 \end{bmatrix}$$

We can do this on the dual problem, on the sites and iron out the differences between sites with respect to their actors

I do not have time to explain the problem in detail but here are the results for the relative power & interest of actors and sites in the problem



Agents

1 City Corporation	17%
2 Residents	6%
3 Hospital NHS	17%
4 Developers	23%
5 Property Spec	25%
6 Banks	10%

Thanks

Michael Batty
Centre for Advanced Spatial Analysis
CASA-UCL

www.complexcity.info
www.ucl.ac.uk/bartlett/casa/

m.batty@ucl.ac.uk
@jmichaelbatty

There is a short article on the last example in

Batty, M. (2016) Evolving a Plan: Design and Planning with Complexity, in J. Portugali and E. Stolk (Editors) ***Complexity, Cognition, Urban Planning and Design***, Springer, NY, 21-42

https://tinyurl.com/rpagr2b

m.batty@ucl.ac.uk
@jmichaelbatty