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By Jason G. Goldman | August 18, 2011 |

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Mathematics, Cite: Brains: What Can A Engineer Learn Fro Neuroscientist?



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At their most fundamental level, brains are made up of neurons. And those neurons collectively comprise the two main types of brain tissue: white matter is made up primarily of axons, and grey matter is made up of synapses, or the connections between neurons. (Want a primer on the neuron? Check out this explainer post by Scicurious)

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The grey matter is highlighted separately from the white matter, and then both images are combined.

Grey matter exists as a thin, relatively flat sheet covering the rest of the brain, and is referred to as the *cortex*. When you compare the brains of different mammal species, you find that certain measurements of brain structure scale in similar ways. In other words, variables like grey matter volume, total number of synapses, white matter volume, number of neurons, surface area, axon diameter, and number of distinct cortical “areas” maintain common mathematical relationships with each other, whether you’re looking at the brains of mice, rabbits, dogs, cats, hyenas, kangaroos, bats, sloths, bonobos, or humans. For example, comparing the brains of different mammal species, for every S additional units of cortical surface area, there is a number of additional neurons N equal to $S^{0.75}$ multiplied by a constant, b . In other words, as S increases, N (the total number of neurons) increases in proportion to $S^{0.75}$.

The specifics aren’t important, so let’s make this a little bit less mathematically opaque: there exists a relationship between the surface area of the brain and the number of neurons in that brain; that relationship can be described by the number 0.75. Similarly, there exists a relationship between the surface area of the brain and the number of synapses in that brain, and that relationship can be described by the number 1.125. There are similar numbers that describe the relationship between the brain’s surface area and the number of synapses per neuron, the average diameter of white matter axons, the average speed at which information travels along axons, and so on.

It may be that these mathematical relationships – or *scaling laws* – are a consequence of evolutionary selection for a sheet-like structure (recall that the cortex, or the brain’s grey matter, exists as a thin sheet resting on top of the rest of the brain). It may be that a thin sheet represents a particularly economical structure that simultaneously allows a high level of interconnectedness across the brain, and a low level of energy needed to support that interconnectedness.

Lots of networks have been compared to urban systems. Remember when the internet was referred to as the *information superhighway*? And high school biology teachers have been [comparing the workings of cells to city operations](#) for decades. To what extent, though, might a **brain** be like a **city**?

Making the Case for Cities and Brains

There’s the obvious analogy: neurons are like highways. Neurons are channels that carry *information* in the form of electric signals from one location within the brain to another, while highways are channels that transport people and materials from one location within a city to another. Cognitive scientists Mark Changizi ([web](#), [twitter](#)) and Marc Destefano ([web](#), [twitter](#)) think that the analogy goes deeper, though: “from the perspective of the city as a whole, the materials and people that highways

Image of the Week



Water flowing on the surface of Mars

Video of the Week



Lilium urbanus - the sprouting of a city

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transport are crucial to the large-scale function carried out by the city, and are, in a sense, signals – that one signal is electric and the other physical may not matter in regards to the fundamental properties governing them.”

State

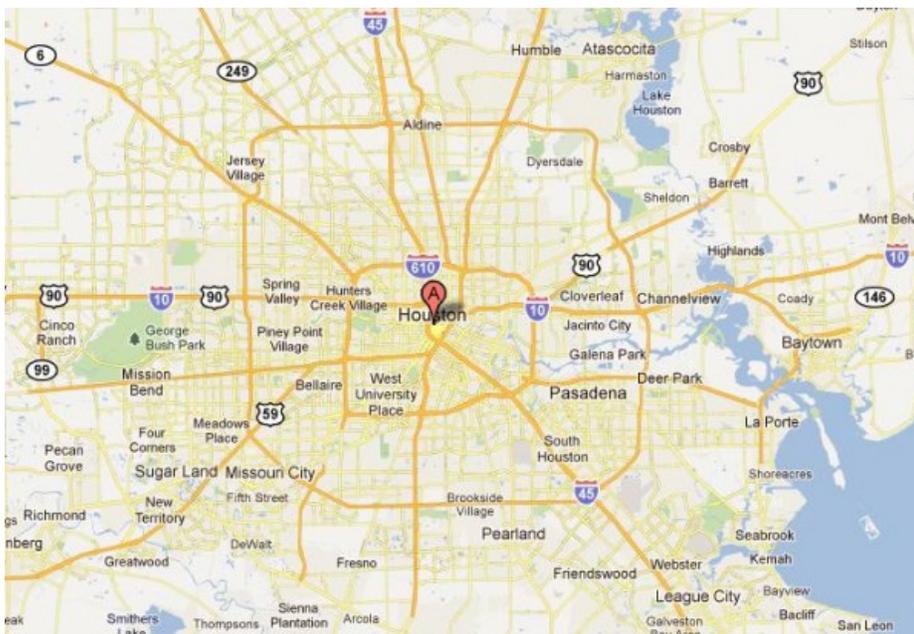
Zip

And that’s not all. They argue that the organization of city highway networks is driven over time by political and economic forces, rather than explicitly planned based on principles of highway engineering – which means that city highway systems may be subject to a form of selection pressure similar to the selection pressure exerted on biological systems. Cities themselves are also under selection pressure to connect with other cities via highways and roads – an inaccessible city can’t survive. Cities are also an appropriate model for comparison with the brain, as they lie on land: a sheet-like structure, just like the cortex.

“Nearly half of Earth’s 6.6 billion people now live in cities,” they write, “and cities are becoming ever larger and densely populated. The proper functioning of a city requires that people and materials be quickly moved throughout it.” City populations tend to increase over time, and at a faster rate than city surface area, meaning that an efficient highway system must continually evolve from pre-existing systems. Cities are starting to sound more and more like brains. Is it possible that city highway systems and the mammalian cortex follow similar scaling laws? If so, it could be that the organization of the brain is just one instance of a more general type of structure found in nature. Changizi and Destefano collected data from 60 cities in the United States, across a wide range of geographic locations and population sizes.

Number of Highways and Number of Neurons

Cities tend to be organized in concentric circles around an urban city center. Some highways, the “spokes,” extend outward from the city center, while other highways (the “rings”) allow travel around the circumference of the city center. The relationship between the surface area of cities and the number of highways that exist in those cities can be described by the number 0.759. This is amazingly close to the number that represents the relationship between the surface area of the brain and the number of neurons: 0.75!



The spokes-and-rings highway system organization is obvious in Houston, Texas, but can be easily seen in most large cities. Head on over to Google Maps and try it out.

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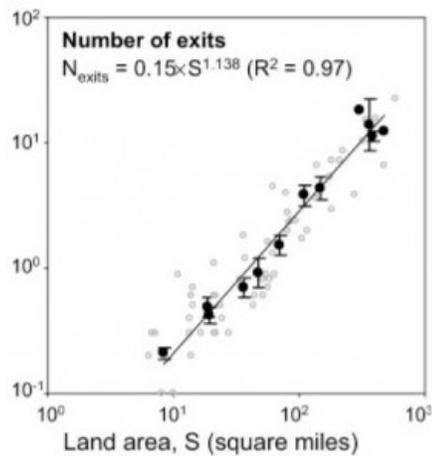
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Number of Highway Exits and Number of Synapses

As information travels along the neuron, it eventually exits in the form of **neurotransmitters** and that information transfers into a new neuron. Likewise, as cars travel along highways, they eventually exit through an off-ramp. Changizi and Destefano calculated that the number representing the relationship between land area and density of freeway exits is between 1.066 and 1.210. When it comes to brain surface area and total number of synapses, that number is 1.125 – which falls right in the middle of the range for freeway exits!

Interestingly, the number of zip-codes and number of public high schools scales similarly to the number of exits, meaning that their surface density increases (1.084 for zip codes, and 1.120 for schools) in the same way as highway exits (approximately 1.183) as city boundaries expand.



The number of highway off-ramps increases at the 1.138 power of land area.

Number of Highway Lanes and Diameter of Axons

One important property of neuronal axons is that many of them are *myelinated*.

Myelin is the white substance that encases the neuron's axon, and gives "white matter" its name. Myelination allows for the faster, more efficient transmission of information across axons. Likewise, increasing the number of lanes in a highway allows for faster, more efficient transportation of people across town. As land area increases, the number of highway lanes increases by a factor of 0.174. As brain surface area increases, however, axon diameters increase by a factor of 0.125, which is somewhat slower than highway lanes. Changizi and Destefano point out, though, that this could be due to the fact that axons exist in three dimensions, while highways are limited to two dimensions. Therefore, for the same increase in efficiency, the highway would need to expand relatively faster than an axon would. Therefore, that the number of highways is larger than the number for axons would be expected.



© Enrique Gutierrez

An empty I-405 is very rare for Los Angeles - but for two days in July 2011, the freeway was closed as part of a multi-year freeway expansion project, sending Angelenos into a state of panic.

Cross-City Travel Speed and Speed of Conduction Across Axons

Changizi and Destefano measured cross-city travel speed by taking the distance traveled and divided it by travel duration, and averaged between two theoretical trips: one across the long axis of each city, and one across the short axis. The number that described the relationship between land area and travel speed was 0.108. For the cortex, the speed at which information travels down axons can be described by the number 0.125 – a difference of only 0.017!

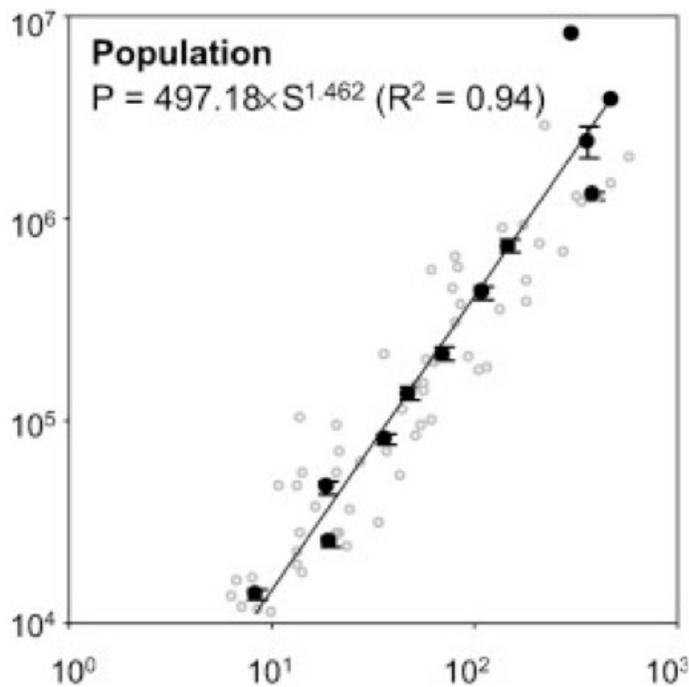
Highway System Surface Area and Surface Area of Axons

As cities become larger, highway surface area increases by a factor of 1.433. Total surface area of white matter axons can be calculated by multiplying the number of neurons, the length of white matter axons, and the axon diameter. The derived surface area of axons, then, scales with brain surface area by a factor of 1.375. Again, this is very close to the number calculated for highway surface area.

Population Size and Volume of White Matter Axons

The number that represents the relationship between the population of a city and land area is 1.462, which means that populations increase faster than the cities can grow in surface area to accommodate them. How do large cities accommodate rapid increases in population size? Changizi and Destefano speculate that since this number is so close to the number for highway surface area (1.433), it may be that highway surface area and population size increase nearly linearly. This suggests that “rather than population being driven by city surface area, population may be being driven by the total surface area of highways, as if each person requires some fixed allotment of highway surface area (e.g. the area required by a car for safe travel).”

An alternative hypothesis is that rather than scaling as the 1.462 power, population actually scales closer to the 1.5 power (which falls within the margin of error derived by the statistical test that resulted in the 1.462 measurement). As it happens, the total volume of white matter axons scales as the 1.5 power of cortical surface area!



Population increases fast relative to cities' land area. Note the 1.462 in the equation at top left.

City Areas and Cortical Areas

One important feature of the brain is that the cortex is separated into distinct regions, which have physical difference in how they are organized, as well as **functional differences**, in terms of what sorts of operations they carry out. This means that neurons in the immediate “neighborhood” likely work on the same sorts of problems – functional areas in the brain such as the “ **fusiform face area,**” or “ **visual cortex**” makes this functional specialization clear. Certain problems can be solved within a single area, rather than requiring cooperation across larger expanses of neural real estate. For the brain, the relationship between the number of cortical areas and cortical surface area can be expressed by the number 0.375.

It should be fairly obvious that cities compartmentalize as well. For example, Changizi and Destefano point out that, “there tends to be a downtown business district, rather than finding these businesses uniformly distributed throughout the city. Such compartmentalization may tend to minimize costs for the infrastructure needed near businesses, as well as minimizing travel costs for business-business and business-infrastructure interactions, **keeping travels short and on surface streets within each functionally specialized area.**” (emphasis mine)

If cities are designed to keep local travel on surface streets, while reserving highway travel for other purposes, then it might be that cities compartmentalize the same way that brains compartmentalize, into various functionally specialized areas. The problem is, it isn't clear how to measure compartmentalization within cities. One possibility suggested by Changizi and Destefano is to focus on the concentric circles surrounding a city center. For example, the map of Houston shown above shows four concentric ring sections. Using this method for compartmentalization, then the relationship between the number of city areas and city surface area would be expressed by the number 0.390. Which is – you guessed it! – tantalizingly close to 0.375.

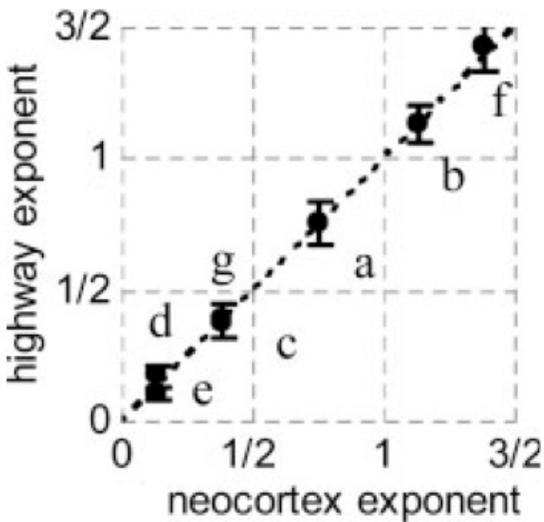


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Downtown Los Angeles at night.

Common City-Brain Scaling Laws

“Cities are not brains,” Changizi and Destefano conclude their paper, “and the metaphor can only be pushed so far.” For example, highways have interchanges, where drivers can transition from one to another; there is no neural analogue for this. That said, the similarities between the way brains grow in scale and the way cities grow in scale can not be ignored. That these two types of networks, which are so different, scale so similarly suggests that they are examples of a more general kind of network that might be found in other places in nature as well.



Perhaps as engineers look to biology for answers for so many other problems in society – such as solar panels modeled on tree leaves or submarines inspired by fish – city planners and highway engineers ought to look to the mammalian brain for answers to the questions that cities will inevitably face as population grows and the number of cars on the roads increases.

**highway systems and the mammalian neocortex *Complexity* DOI:
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Images: White matter/grey matter image [source](#); Houston map via [Google Maps](#); Carmageddon photo by [Enrique Gutierrez](#), used with permission. Top photo of downtown LA freeways and Downtown LA at night copyright the author. All other images from Changizi and Destefano (2009).

This post is a contribution to this month's *Scientific American* theme, which is Cities. The articles from the print mag, as well as many more Web-only features and blog posts, are being unrolled on the site all month long. See more at the [Cities](#) page.



About the Author: Jason G. Goldman is a graduate student in developmental psychology at the [University of Southern California](#), where he studies the evolutionary and developmental origins of the mind in humans and non-human animals. Jason is also Psychology and Neuroscience Editor for [ResearchBlogging.org](#) and Editor of [Open Lab 2010](#). He lives in Los Angeles, CA. Follow on Twitter [@jgold85](#).

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