Classifying the *Caenorhabditis Elegans* Neural Network

1.041 Transportation Systems Modeling

Submitted by

Anna R Falvello Tomas and Mun Ngah Cheong

Massachusetts Institute of Technology

Spring 2013

Table of Contents

List of Figures

List of Tables

Introduction

The neural network of the nematode worm *Caenorhabditis elegans* has received considerable attention as a model organism in neurobiology. The *C. elegans* wiring diagram used in this study consists of 306 neurons (or nodes) and 2345 connections (or edges). The nodes represent neurons, and the edges represent either a chemical synapse or a gap junction. It should be noted that the data was compiled by Watts and Strogatz (1998) based on the original experimental data taken from White et al. (1986).

We chose this network because of our scientific interest in the relationship between biology and network theory and because there has been extensive literature written on this topic.

Literature Review

Previous research works (White et al., 1986) have described parts of the adult *C. elegans* nervous system in detail.[1] Several studies (Watts and Strogatz, 1998; Varshney et al., 2011) have shown that the *C. elegans* neural network to be **small world network.**

Varshney et al. (2011) proposed a method to visualize the wiring diagram of *C. elegans* network that helps explain the network signal propagation as well as the closeness of neurons in the network. For the gap junction network, Figure 1 shows that the tail ($d \geq 4$) can be fit by the power law with exponent $= 3.14 \pm 0.13$, but not by the exponential decay ($p < 0.1$). Based on this result, **the gap junction network is scale-free**.

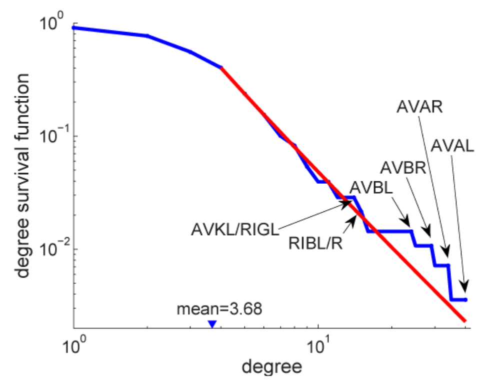

Figure 2: Degree Distribution of gap junction network in *C. elegans*. (Varshney et al., 2011)

> "The tails of the degree and terminal number distributions for the gap, chemical and combined networks (with the exception of the in-numbers) follow a power law consistent with the network being scale-free in the sense of Barabási and Albert. The tails of some distributions can also be fit by an exponential decay, consistent with a previous report. However, we found that exponential fits for the tails have (sometimes insignificantly) lower log-likelihoods than power laws, making the exponential decay a less likely alternative."
>
> (Varshney et al., 2011)

[1] The adult *C. elegans* hermaphrodite has 302 neurons that belong to two distinct and

Analysis

The first step of our study was to try and classify the *C.elegans* neural network. In order to do this, we compared the properties of the *C.elegans* network to those of a synthetic random graph (RG) of equal N and <k>. This random graph was generated with the following *p*:

$$p_{directed} = 2 * \frac{c}{n-1} = 2 * \frac{7.7}{306-1} = 0.05$$

We then compared the clustering coefficient, C(p), and average path length L(p) of the RG to those of our neural network, as seen in Table 1.

Table 1: Comparison between *C. Elegans* and Random Graph

	C. Elegans	Random Graph
Clustering Coefficient	0.164	0.024
Average path Length	4.0	2.8

As described by Watts and Strogatz (1998), there is a regime between $0<p<1$ where the average path length of a network is almost as small as that of a RG, yet the clustering coefficient is a lot larger than that of a RG. The *C.elegans* network falls exactly in this regime, also known as the Small World (SW) category. In fact, all of the literature we encountered categorized the *C.elegans* neural network as a Small World, leaving us with little doubt that this classification is correct. However, we wished to analyze our network in more depth, given that SW includes a broad range of network typologies.

Comparison of network properties. As an initial step, we compared the network properties of the *C.elegans* to our reference scale-free (SF) network and RG, as seen in Table 2.

Table 2: Summary table

Properties	C.Elegans	Scale Free	Random Graph
Nodes	306	309	306
Links	2345	3594	2271
K_{max}	134	368	26
<k>	7.6	11.6	7.6
Clustering Coef.	0.164	0.33	0.025
Connected components	10	1	1
Average Path Length	4.0	2.5	2.8

The property that stands out most is the maximum degree (K_{max}) of the *C.elegans* network. It is a lot larger than the K_{max} of the RG, yet it is not as large as that of our reference SF network. This hints that perhaps the *C.elegans* network may present some SF characteristics.

Assortativity. Secondly, we searched for traces of assortativity within our network. To this end, we plotted degree (k) against the average degree of a node's neighbors (K_{nn}), and compared it to that of a reference SF network (see Figure 2).

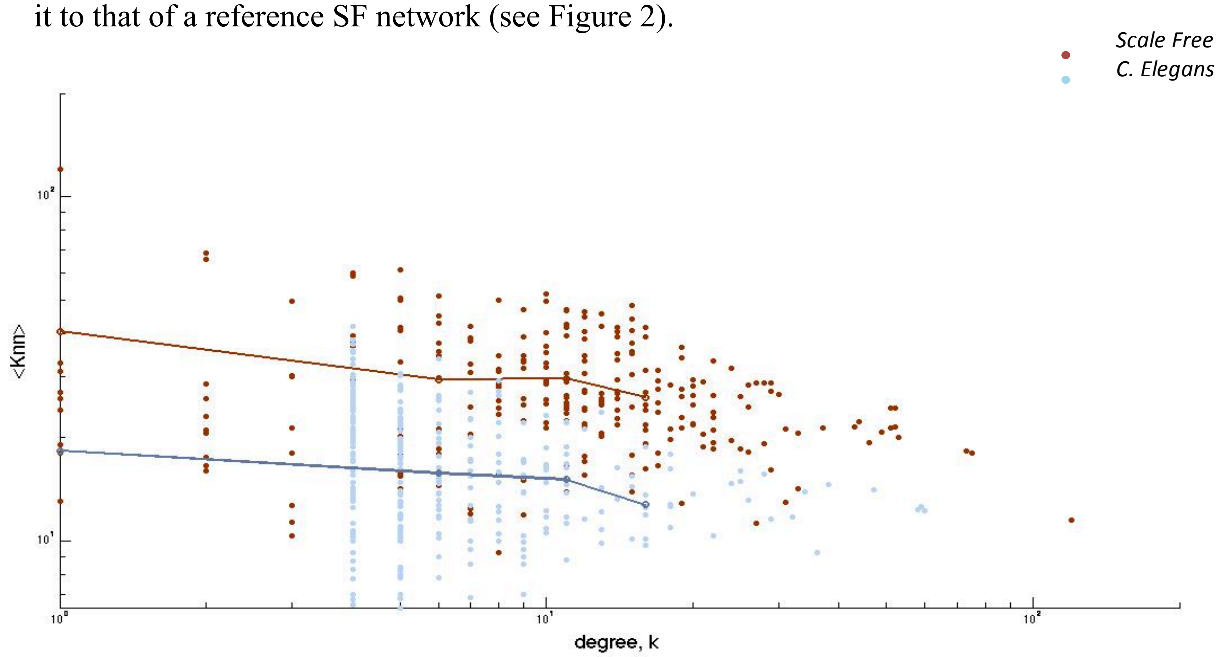

Figure 1: Degree vs. average degree of a node's neighbors

Had our network been assortative, the blue curve in this graph would have been increasing and, in fact, we find exactly the opposite. If anything, the *C.elegans* neural network is dissortative. While we haven't found out exactly why this is, or how dissortativity relates to the actual functioning of neural networks, we have found sources that classify neural and protein networks as dissortative (Ben-Naim et al., 2004). This is in contrast to social networks, for example, which tend to be assortative.

Type of Small World. The last step of our study tried to identify our network as one of the three SW typologies that Amaral et.al describe in their paper: scale-free, broad scale or single-scale. For this, we plotted our degree distribution in *log-log* and *log-linear* scales (see Figure 3).

The *log-log* graph shows a linear fit in the tail of our degree distribution. This type of linear fit is typical of power-law networks. In order to confirm that this tail does follow a power-law, we plotted the same distribution on a *log-linear* scale, and zoomed in on the tail. Indeed, we found a power-law type fit for degrees k>20. The only difference between this tail and a true power law is that the *C.elegans* distribution has a sudden cutoff at a K*max* of 134 while, in theory, a truly power-law tail would continue to decay.

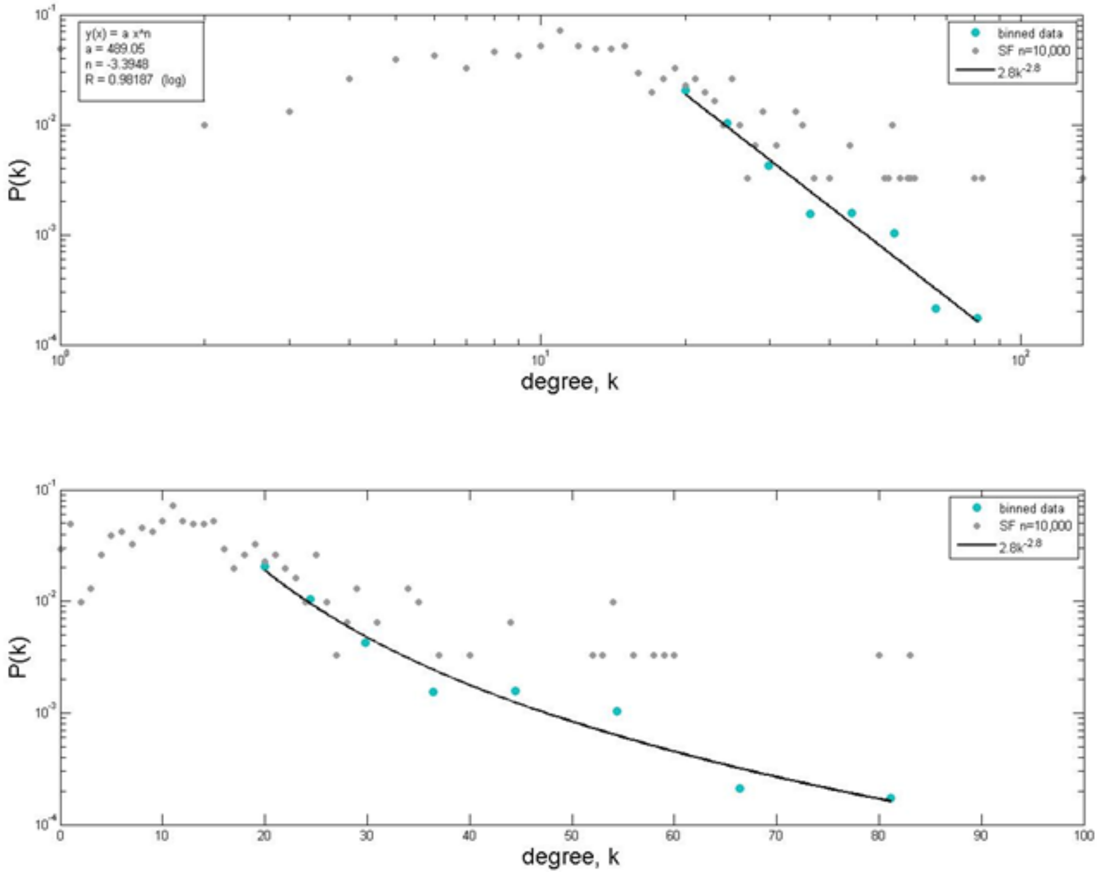

Figure 2: Degree distribution --- log-log graph (top) and log-linear graph (bottom)

Future Works and Conclusions

These findings do not allows us to classify the *C.elegans* neural network in an absolute manner, given that only its tail follows a power-law type decay, and it presents a sudden cutoff at k = 134. What we can say is that this network is a dissortative, SW network with a seemingly Gaussian degree distribution for approximately k<20, and a power-law type distribution for k>20. In other words, it is not always possible to classify a network in a predefined category but rather; hybrid type networks may also arise.

In the future, we would suggest studying the relationships between the network properties of the *C.elegans* neural network and the macroscopic behavior of the actual neural network further. For example, how can neural behavior be related to the fact that hub-like nodes appear, or to the fact that neural networks are dissortative?

Methods

Datasets used:

- *RandomGraph.gephi*. Directed random graph generated using Gephi, with 306 nodes and average degree 7.6 (p = 0.05).
- *CElegans.gefx*. Directed graph with 306 nodes, based on data from White et al. (1986)
- *ScaleFree.csv*. Originally *sf_m4_306.csv*, given in class. Scale Free network with n=309.

Programs used in this study:

- **MATLAB**: to generate graphs, bin data, and fit functions to our plots.
- **Gephi**: outputs the network parameters of interest and visualizations.
- ***Processing***: Using the script *WriteNetwork.pde*, we were able to calculate K_{nn}.

References

Amaral, L., Scala, A., Barthelemy, M., and Stanley, H. (2000). Classes of small-world networks. PNAS. 97(21). 11149-11152.

Ben-Naim,E., Frauenfelder, H. and Toroczkai, Z. (2004) . Complex Networks, Lect. Notes Physics. 650. (Springer, Berlin Heidelberg). 115.

Hall, D. H., & Russell, R. L. (1991). The posterior nervous system of the nematode caenorhabditis elegans: Serial reconstruction of identified neurons and complete pattern of synaptic interactions. *The Journal of Neuroscience*, *11*(1), 1-22. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1986064

Varshney, L. R., Chen, B. L., Paniagua, E., Hall, D. H., & Chklovskii, D. B. (2011). Structural properties of the caenorhabditis elegans neuronal network. *PLoS Computational Biology*, *7*(2), Retrieved from http://www.ploscompbiol.org/article/info:doi/10.1371/journal.pcbi.1001066

Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of 'small-world' networks. *Nature*, *393*, 440-442. Retrieved from http://www.nature.com/nature/journal/v393/n6684/abs/393440a0.html