

BRAIN SCIENCE PODCAST

With Ginger Campbell, MD

Episode #74

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Interview with Olaf Sporns, PhD, Author of *Networks of the Brain*

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“There’s really nothing boring about the brain. If you want to pick a scientific subject that’s really exciting right now, and where almost everything that we do and explore has very immediate real-world consequences for the brain—how we understand how it works in health, but also in disease—this is a really fabulous subject to really sink your teeth in.” Dr. Olaf Sporns, *Brain Science Podcast #74*

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INTRODUCTION

This is Episode 74 of the *Brain Science Podcast*, and I am your host, Dr. Ginger Campbell. My guest today is [Dr. Olaf Sporns](#), author of [Networks of the Brain](#). I’ll tell you more about that in just a minute.

But first I have an announcement that I hope will please loyal listeners. Beginning on July 1, 2011, a new episode of the *Brain Science Podcast* will be coming out every month, around the first Friday of the month.

Also, I want to remind you that you can get detailed show notes, links, and episode transcripts at our website at brainsciencepodcast.com. You can send me email at docartemis@gmail.com, or leave voicemail at 205-202-0663.

I'm going to play today's interview with only one break, so I also need to mention that the *Brain Science Podcast* is made possible by [donations](#) from listeners like you, and by the sponsorship of Audible.com, the world's leading provider of downloadable audiobooks. If you aren't already a member, you can get a free audiobook download by going to audiblepodcast.com/brainscience.

Before I play this month's interview, I need to make a few comments. First, if you are a new listener, don't be intimidated by the technical nature of today's discussion. Even if you have a background in neuroscience you may find the first 10 minutes of the conversation a little tedious, but it provides all the background information you really need to understand the rest of the discussion. While I think this episode will be of particular interest to people working in neuroscience, math, or computer science, it is intended to introduce everyone to a field that I am sure will be of increasing importance in the future.

[Network theory](#) is the application of the mathematical field known as [graph theory](#) to real-world problems like power grids and the Internet. It provides a way of exploring the connectivity of the brain, and it is an extremely powerful tool for coping with the massive amounts of data that are being generated by our new measurement tools. The book, *Networks of the Brain*, by Olaf Sporns, provides an excellent introduction to this important field.

Unfortunately, the sound quality of today's interview is less than ideal. If you have trouble hearing, don't forget that you can get the episode transcript at our [website](#), or via the *Brain Science Podcast* app, which is now available for [iPhone](#), [Android](#),¹ and [iPad](#).

¹ The *Brain Science Podcast* app is also [featured in the new Amazon app Store for Android](#).

Please continue listening after the interview, when I will summarize the key ideas, and also make a few announcements.

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INTERVIEW

Dr. Campbell: Olaf, I want to welcome you back to the *Brain Science Podcast*, and thank you for taking the time to talk to me again.

Dr. Sporns: Thank you.

Dr. Campbell: Could we start out by just letting you tell us a little bit about yourself?

Dr. Sporns: Yes. My name is Olaf Sporns. I am a professor here at [Indiana University](#). As you can hear, perhaps, from my accent, I was actually born in Germany. I grew up there, and went to school in Tübingen, in the southern part of Germany, and studied biochemistry.

I then became interested in neuroscience, and pursued a PhD in neuroscience at [Rockefeller University](#) in New York, and became involved in simulations of brain networks—of simple representations of nervous systems. So, I kind of pursued a double track of empirical and computational research for the past 20 or 25 years, really.

I moved to San Diego for a postdoc, and then a research scientist position there. Finally, about 10 to 12 years ago, I moved to Indiana to take a position here in the [Department of Psychological and Brain Sciences](#).

Dr. Campbell: What motivated you to write your book, *Networks of the Brain*?

Dr. Sporns: I wanted to introduce the two fields of neuroscience and network science in context, because there are growing lines of collaboration and confluence between these two fields, but there really hasn't been a book-length account of how these two fields relate to each other. And my work has always been in both of these areas, so I wanted to give readers an introduction into the emerging area of applications of network science to neurobiological questions.

Dr. Campbell: What's the intended audience of your book?

Dr. Sporns: I'm really thinking of my audience in very broad terms: Certainly graduate students, but also undergraduates who might be interested in this subject; researchers who are actively pursuing work in either network science, or computer science, or neuroscience. I'm thinking of people who have an interest in the nervous system in general, and who might find this an appealing way into learning something new about the subject.

Dr. Campbell: One thing I've learned from doing this podcast is that it is surprising how many people will read technical books, who are people that are outside the field, that you would have never guessed would do it.

Dr. Sporns: Yes.

Dr. Campbell: When I [interviewed](#) the author² of *Rhythms of the Brain*, that book was recommended to me by a listener whose professional field is physical therapy. And, boy, did I almost get myself in over my head.

Dr. Sporns: That's a technical book. I happen to know that book quite well, and I also know the author quite well. It's a great account of a whole big swath of neuroscientific research, written at a very high level and very technical, but I

² György Buzsáki was interviewed in [BSP 31](#).

think also very accessible. In fact, his book is a good example of the kind of book I wanted to create also.

Dr. Campbell: Yes; and I think your book succeeds in that regard, definitely.

Why is it that network theory is an important tool for neuroscience?

Dr. Sporns: Actually there's a wider context here. Network theory, or the idea that networks can be useful for understanding natural or social systems, that idea already has a long history. And networks have been applied in various contexts—from social systems, to the economy, all the way to cellular biology and molecules, and so forth—for a very long time, now. So, it's a natural extension of the range of network theory.

The brain naturally is a network of neurons that are interconnected. And so, the application is actually pretty straight-forward. For various reasons, there hasn't been that much work done until a few years ago, in neuroscience, in the same spirit of network approaches. But I think that's changing now, and I think it's a very fruitful way of looking at the brain.

Dr. Campbell: I came away from your book with an appreciation of the fact that this is a tool that helps us to deal with the brain's complexity, and also helps us to deal with the vast amounts of data that are being generated by these new techniques like [brain imaging](#).

Dr. Sporns: Yes, you're absolutely right. I think we're undergoing a big change right now in various parts of neuroscience. It used to be, until a few years ago, research was done primarily in relatively small laboratories, where data was preserved locally—not shared, really. But we're moving into a new era now, where we have a lot more collaborative projects, and where a lot of the time now, data is made publicly available.

And we're getting huge amounts of data from brain recordings—from brain imaging, as you mentioned. And so, we need something like a quantitative framework to integrate all these data together. This is totally in parallel to the kinds of developments that have taken place in other parts of biology; for instance, in [systems biology](#), where there is a real need to integrate genomic data, behavioral data, molecular data, and so forth, to make sense of it. So, I think that you're absolutely right, that's sort of a driving force for applying these approaches to the brain.

Dr. Campbell: Another key idea that comes up often in your book is the idea that the brain is a multiscale system. Would you talk a little bit about that concept?

Dr. Sporns: Yes, that concept is sort of important to me. I want to think of the brain, not so much as being reducible to the functioning of elements at one scale only; for example, the functioning of individual neurons. Really it's neurons that we need to study, but then also interactions between neurons that give rise to circuits and populations; and then beyond that, to entire systems—large-scale system— of whole brains and how they're connected to bodies in the environment.

There are multiple nested scales that are involved here, and I think all of these scales together are important for understanding how the brain works. So, I really wanted to underscore that point. And network science is sort of a nice way of framing the multiscale organization, and making it accessible and quantifiable.

Dr. Campbell: Let's talk a little bit about some of the basic concepts of network theory. I guess the first question I have is what's the relationship between graph theory and networks?

Dr. Sporns: I think ‘networks’ might be a broader term, and is often applied to real-world systems like a power grid, or the economy, or cells, and so forth. Graph theory refers to a quantitative approach—a branch of mathematics, really—that deals with specific mathematical objects which are graphs; which are collections of nodes and edges. The nodes are the elements, and the edges are the connections between them. And those mathematical objects can be studied in very exquisite detail with all sorts of tools—computational tools, analytic tools. Graph theory and mathematics are very well developed fields that we have only just begun to tap into to utilize what’s available there for our purposes.

Dr. Campbell: Are there some particular concepts from graph theory and its use in networks that are most relevant for understanding, say, the functional organization of the brain?

Dr. Sporns: One of the long-standing principles of the architecture of the brain (certainly the [cerebral cortex](#)) has been that there’s a coexistence of what people have called ‘functional specialization’—the existence of specialized regions that accomplish specific tasks—and then, their integration in a distributed network; the interactions between them, which are mediated by axonal fiber pathways in the brain. And so, we’ve been having this view of functional segregation, or specialization and integration, for a while.

And I think graph theory and networks, in general, now allow us to express this framework, computationally and analytically, actually quantifying different aspects of this. By using various graph theoretic tools, we can now take a brain network and we can quantify to what extent is information, for instance, broken down into pieces, and to what extent can it be integrated.

Dr. Campbell: Is that where the idea of the [small-world architecture](#) comes up?

Dr. Sporns: Exactly. That's actually very relevant here in this context. The discovery of the 'small world' really goes back several decades, and is rooted in the social sciences. About a dozen years ago or so, a very influential [paper](#) appeared, written by [Duncan Watts](#) and [Steve Strogatz](#), in which they presented a very simple quantitative model to actually describe the small-world architecture³. There were two key ingredients: high clustering and a short path length. The high clustering sort of maps onto what we were talking about earlier, about functional segregation. It sort of quantifies the extent to which a network is broken up into local communities.

And then, the path length taps into the other aspect of brain organization, which is integration. Path length means how many steps do I need to move from any one node to any other node, on average. And if that's a short path length, I have a relatively easy way of transmitting information across the network.

Dr. Campbell: Were they the ones that showed that the [C. elegans](#) nematode has a small-world architecture—its nervous system?

Dr. Sporns: Actually they did perform the first analysis. In their 1998 paper they performed the first analysis of the cellular network of *C. elegans*, as well as other networks. I believe the power grid and a few other technological networks were investigated in that paper. And yes, they were the first ones who actually pointed out that there is a small-world organization in that very simple network of around 280 to 300 neurons.

Dr. Campbell: It never ceases to amaze me how much we really have in common with even the most simple life forms.

Dr. Sporns: That's actually an interesting point you're making, because we keep coming across some of the same features of network architecture when we

³ Watts, DJ, Strogatz SH. "Collective Dynamics of 'small-world' networks." *Nature* [393: 440-442](#) (1998).

look at very different brains. There may be a very deep message in there about what certain architectures can do for us, in terms of information processing.

Dr. Campbell: Yes; and we're going to talk about that some more in a little while. But I did want to ask you—because I'm sure that some of my listeners are going to be wondering—what kind of mathematical background does a person need to be able to master the tools of network theory?

Dr. Sporns: I think one can get started with a relatively modest amount of mathematical background. In fact, I wrote the book, as you know, without using any mathematics—there are no equations in it—because I wanted people to get an intuitive understanding of some of the key concepts.

Actually applying these concepts in a professional setting, working with data, and so forth, requires a little bit of training, a little bit of familiarity with basic concepts of math, and graphs, and so forth. But, at least at a very simple level, it is quite possible to get a feeling for, and perhaps begin applying these techniques. They're actually very intuitive, I think. They map very nicely on an intuitive understanding that we might have about how these networks function.

Dr. Campbell: And you have developed software that you share with other people that are working in this field?

Dr. Sporns: Yes. I've worked on applications of graph theory, really for quite a long time now, in neuroscience. And one of my strategies early on was to make the tools that I developed for myself available for the community. And so, for about 10 years or so, I've been maintaining what is called a [Toolbox](#), which is really a set of functions and algorithms that people can get off the Web for free, and can use in their own work.

I think it's very widely used. I'm getting a lot of feedback from people out there who are using it, so I know how many people must be working with it. It's

actually very gratifying to see so many people appreciating that they can get a relatively easy start with the software I can provide.

Dr. Campbell: So, I guess we are ready to talk a little bit about how you actually do this stuff. Would you talk a little bit about how the network approach fits into the historical arguments about brain organization?

Dr. Sporns: Historically one of the many controversies that we've had in neuroscience revolves around the issue of functional localization. That goes back, certainly, to the 19th century; perhaps earlier than that. And there have always been sort of two different viewpoints on that. The first viewpoint is that brain regions, perhaps individual neurons, carry out very specific tasks; very specific mental faculties are represented in them. And then there was the opposing view that said that's really not the essence of the story; it's all much more distributed.

And I think the network approach, using network science as a guiding post here, sort of resolves that nicely; because really it's some of both. We have some functional specialization, which is conveyed in part by the connections that elements have. Neurons and brain regions have different patterns of connections with each other, and it is those connections that ultimately endow them with their functional capacities.

And then, of course, function is distributed. There's, I think, no mental function we can think of right now that is carried out exclusively by one piece of the brain. So, we have networks that are naturally overlapping with each other, that involve regions and neurons that are somewhat specialized to carry out certain parts of the task. But it's not totally localized to individual units.

Dr. Campbell: Could you talk a little bit about how brain networks are constructed? What I have in mind here is the different types of connectivity that you might want to study, and how they differ.

Dr. Sporns: The topic of brain connectivity is really a very large topic. It involves networks at least at three different levels. At one level we have physical networks of connections—physical connections in the brain; synapses, and axonal pathways, and all of that. On the other hand, we also can construct networks from observations of the brain that are carried out using recording techniques like [fMRI](#), [EEG](#), or [MEG](#).

Those will yield time series of neuronal activations, and those can be converted into networks. These are typically called ‘functional and effective networks.’ So, we have on one side anatomical networks, on the other side, functional and effective networks. And there are actually interesting relationships between the two.

Dr. Campbell: And they’re based on different data.

Dr. Sporns: Yes, they’re very different measurement techniques. In the case of the human brain, for the anatomy, quite often people now use something called [diffusion imaging](#), which is a noninvasive imaging procedure that reveals to us the trajectories—the paths of fibers in the brain⁴. And for functional networks quite often people use functional MRI, which is a very widely-available noninvasive recording technique now that allows us to track neuronal activations across time in the human brain.

Dr. Campbell: One of the principles you talk about that I think is probably worth spending a couple of minutes on is the fact that you talk a lot about the different measurement techniques, and the differing levels of resolution of these measuring techniques, and how that limits or determines how the networks are generated at this point in time.

⁴ Brain imaging, including diffusion imaging was discussed in [BSP 46](#).

Dr. Sporns: Yes. I think, as practitioners applying network approaches to the brain, we have to be very sensitive to what our measurement techniques really tell us about the underlying neurobiological reality. It is not possible—certainly not in the human brain—to observe neuronal events directly. We’re obviously not going to cut somebody open and look at their neurons, one by one.

We have to record from a distance; from the outside of the brain. And there are many steps involved that will, in the end, impact our interpretation of what we’re actually measuring. I think the practitioners in this field need to be—and I think, for the most part, are—very sensitive to being very clear about what they’re measuring, how they’re measuring it, and what the network really then tells them about what’s really going on in there.

Dr. Campbell: So, for example, when you’re doing stuff about anatomy you’re talking about things that are relatively stable over time, as opposed to functional connectivity, which is much more transient, right?

Dr. Sporns: You’re absolutely right. With the techniques that we have available now to track anatomy, the anatomy that we’re tracking doesn’t change much. Actually, I should say we don’t have much data yet, in a longitudinal setting, to really determine how much the anatomy—even at the large scale—is changing. Perhaps some of it is; but not as fast, certainly, as—as you’re mentioning—functional connectivity.

The way that brain regions are interacting with each other dynamically—neurons becoming active all the time, turning on, turning off, expressing dynamic relations with each other—those networks are blindingly fast. They operate, probably, on time scales that are in the millisecond range—tens or hundreds of milliseconds. So, tracking those across time, it’s very challenging. And it’s actually a fairly unexplored part of the endeavor, still. We’re still discovering how

much change really takes place. And we're trying to track it using network approaches.

Dr. Campbell: So, there's lots of work there for anybody that wants to get into this field.

Dr. Sporns: Oh, yes! And part of the reason for writing the book was to draw people into this, because it's going to be a very interesting and exciting area, I believe.

Dr. Campbell: What about the role of [computation](#) and [computer simulation](#)?

Dr. Sporns: From my perspective, I think it's going to take a more prominent role in the future than it has taken in the past; in part because of what you mentioned earlier. We get so much data now, we need to make sense of it. And it's not possible, sometimes, to describe these data in a very neat fashion, that is analytic, and perhaps you can write down in one equation, or something like that.

We have to employ computational techniques that actually are [instantiating](#) some of these data; look for relationships, attempt to identify a model that can explain the data, and then generate predictions, using the model, for future experimentation. So, I think, as has been the case in other parts of biology—certainly in other sciences—computation will become a more important part of the equation as we move forward.

Dr. Campbell: Yes, I really came away with an appreciation for the fact that this is an [iterative process](#). You use the data to build the graphs, then use those to make predictions, which gets more data, which then leads to better models, which, hopefully, give you more refined predictions; and around and around.

Dr. Sporns: That's an iterative process; you're correct. There's no final model of the brain, and there will never be one—I think. Models are always

approximations; they are based on what we know right now—hopefully. If they're well-constructed, they are going to be able to generate predictions. Those will be tested. More data will be generated. The models will not survive that process; they will have to be changed, updated, increased in size, perhaps made more compact, if we're lucky.

So, it's a constant process of iteration. In some sense it is actually a scientific process itself, because that's how we make progress in science. We ask questions, and the questions we ask are informed by some understanding of how our system works, which is based, in many cases, on a model of how the elements that we're observing interact with each other.

Dr. Campbell: Let's talk a little bit about what we have learned so far. I thought we would start out by talking a little bit about what you have learned about brain anatomy.

Dr. Sporns: I think that, partly as a result of the arrival of these noninvasive diffusion imaging approaches, brain anatomy—especially of the human brain—is really experiencing a renaissance right now. When I was taking classes in medical school, anatomy was a very boring subject. I remember it was not the most exciting thing I looked forward to. But it turns out anatomy is becoming much more exciting again, because we have access to the connectivity of the brain, for instance, in unprecedented detail now.

There are a lot of new things to be discovered, still. I think we're just beginning to get a glimpse of how variable our brains actually are; how much they differ in the way they're connected, across individuals in the population. And there are very interesting questions to be asked here about how do these variations in brain structure relate to differences in behavior and cognition.

Dr. Campbell: One of the things you talked about in your book was the idea of [degeneracy](#), which is something that seems to be ubiquitous in the biological world, but it's not a feature we see in engineered systems. Could you talk about that a little bit?

Dr. Sporns: Certainly. I was very attracted by the work of [Eve Marder](#), who has studied the way in which circuits function—the way they rhythmically organize their activity, for example—how that can depend on many different combinations of parameters of channels and of neurons and how they're connected. I think it's referred to in this work as 'functional homeostasis,' but it's also an example of degeneracy: having many solutions that give you, in the end, a similar or perhaps an identical outcome.

And that's something that certainly we don't want to embody in technology. In technology we want to build systems identically, and we want them to perform identically. But biological systems don't operate that way, it seems. They seem to care about the functional output, but they don't seem to care that much, within limits, how that output is actually generated.

Dr. Campbell: Yes, I [interviewed Dr. Marder](#) a couple of years ago⁵. It was really quite amazing. She spent, I think, 30 years studying the [somatogastric ganglia](#) in the lobster. The stuff that she's discovered is, like you said, quite amazing. And it brings us back to what we talked about before, about how so many of these fascinating things go back even to simple life forms that we don't generally identify with. I mean I don't think lobsters have brains, per se; but they have the ganglia, and they have this variability. I'm trying to remember, but I think she said that the circuit models predicted this variability, and then she went in and tested, and discovered that, in fact, it did exist—because that was against expectation.

⁵ Eve Marder was interviewed in [BSP 56](#).

Dr. Sporns: Yes, I believe that was the story. And it's a very exciting story, because I certainly remember the day when years ago we thought, as simple-minded students of the brain, that vertebrates surely are very simple things. And they have only a few thousand neurons, perhaps a million neurons, something like that. And that's a small-size nervous system. They're very stereotypic; they're like little robots.

And it turns out that that's not the case. The richness of nervous system structure in invertebrates—you mentioned the lobster; I'm looking a little bit now at the fruit fly, *Drosophila*—it's really fabulous to see the richness of the structure, the variability that has not really been charted, so far; at the same time, the functional stability, the robustness of these systems, that it can accomplish very complex information processing tasks with such reliability. So, there's really a lot to be discovered, still.

Dr. Campbell: And, as you also pointed out in your book, the wiring diagram alone is not enough; even though that's something to work toward.

Dr. Sporns: Yes, I think it would be simple-minded to reduce the brain to a wiring diagram. That's certainly not my intention, and I think it would be simple-minded if one were to propose that. You mentioned the worm, *C. elegans*, earlier. It has about 300 neurons—something like that—fairly stereotypically connected to each other. And we've known that particular wiring diagram now for 25 years, as a result of the heroic efforts of researchers who reconstructed this meticulously in the early '80s. But we still don't really understand how the nervous system of *C. elegans* works in its entirety.

So, it is something that we need to know—sort of like the genome. We really do want that information. But it doesn't fully explain the functioning of the organism or of the nervous system; it only gives us a foundation. It's necessary, but not sufficient.

Dr. Campbell: Yes, I remember when they used to think that if we had the human genome, we'd all of a sudden have a lot more answers. And it turned out to be more complicated.

Dr. Sporns: Yes. But none of us wants to go back to a time when we didn't have the genome. It was an enormous step forward, in the right direction. It was sold at the time under somewhat optimistic premises: it would explain everything. But it didn't. However, it now allows us to ask questions that we really haven't been able to ask before.

We simply have to acknowledge the fact and live with the fact that living systems are complex, and that this complexity will not reduce to a simple set of answers any time in the future. I don't believe this will ever really happen. But we will get a better handle on dealing with the complexity, and understanding that, and maybe working with it, as opposed to against it.

Dr. Campbell: Yes. That sounds good to me.

We're going to take a quick break, and then we're going to come back and talk some more about the brain's small-world architecture.

[music]

Dr. Campbell: Olaf, I was wondering if you could talk a little bit more about the brain's small-world architecture, and why that's significant.

Dr. Sporns: The reason why small-world architecture is so significant for the nervous system is because it maps nicely onto what we had mentioned earlier—the idea that there is both functional specialization and also functional integration going on in nervous systems, in general. A small world actually accomplishes both of these constraints, or both of these tasks, very nicely. It provides for the existence of clustered connectivity—clustered connections, which

involve local communities of areas or neurons that are cooperating—and it also allows for the existence of these short paths across the network which allow these communities to actually exchange information, if they want to, very expeditiously.

So, the small-world arrangement provides us with structure on one side, functional specialization, and also with the ability to link these things up and integrate, and create coherent states, which is really important for the brain. So, that's why I think there is something to it that really makes it very appealing for understanding how brains function.

Dr. Campbell: And as far as we know so far, all the nervous systems studied are small worlds.

Dr. Sporns: There have been no exceptions, as far as I know. And I would be very surprised—I think it would be a big discovery, really—if there ever was a nervous system that wouldn't show this organization. I think there are some underpinnings of the small-world architecture that perhaps have something to do with developmental mechanisms—with the fact that neurons are embedded in three-dimensional space. Brains are three-dimensional objects; they have to take up volume, and so forth. And these constraints, which are really physical constraints on how brains are built, I think are powerfully shaping the [topology](#) of the connections, as well.

Dr. Campbell: Are you spending most of your time studying mammalian systems?

Dr. Sporns: I would say yes. I have a growing interest in invertebrate nervous systems, but now, with the inception of the [Human Connectome Project](#), it's mostly human brains.

Dr. Campbell: OK. Narrowing down to mammals for a minute, is there something, in terms of networks, that makes the mammalian brain different?

Dr. Sporns: Different from non-mammalian brains?

Dr. Campbell: Yes; like say, the *C. elegans*.

Dr. Sporns: There is obviously a size increase, and so forth, but it's sort of comparing apples and oranges a little bit. The [nematode](#) brain is composed of single neurons, and we've mapped these single neurons completely. But we really don't have any diagram of single neurons yet for any piece of the mammalian brain; at least none that is really precisely derived from reconstructions. We have some statistical descriptions, but we don't know much beyond that.

Now, at the large scale there are differences, perhaps, in the way mammalian brains are laid out. But I think it's too early to really come to conclusions in a comparative setting. We don't have enough species yet. I hope that there will be more work done in the area of comparative studies of brain anatomy, across the entire range of mammalian brains, but also vertebrates and invertebrates, quite frankly, because we don't have very many data points yet to really have any conclusions about that.

Dr. Campbell: Oh, OK.

One of the chapters that I found most interesting in your book was the one about the spontaneous brain activity. Can you talk a little bit about what we've learned from applying network techniques to this?

Dr. Sporns: The fact that the brain is spontaneously active has been an established fact for, I would say, almost a hundred years; going back to [Hans](#)

[Berger's](#) studies in 1929 of human brain rhythms⁶. But I think in the past couple of decades we've forgotten about that just a little bit, perhaps, in human neuroscience, because we were so focused on the kind of activation studies that have driven functional MRI research—the fact that you can show the activation of fairly circumscribed regions of the brain that are specifically active to particular paths of stimuli.

I think that has driven sort of a mental image of the brain where the brain is sort of quiescent, and waiting for input, and when input arrives something turns on. And that's really not the whole story. We're now discovering that the brain is much more active than that, even at rest. In fact, resting brain activity is now routinely measured in many laboratories, because it's extraordinarily informative about how the brain is organized.

And the kinds of perturbations that paths of stimuli induce are very small perturbations; almost like little ripples on the surface of a swimming pool when you throw in a pebble. They're very small perturbations. They may be very important perturbations—don't get me wrong—but they're really changing an ongoing dynamic structure, and perturbing it, rather than actually turning anything on or off.

Dr. Campbell: Can you talk a little bit about what you call in your book the 'default core?'

Dr. Sporns: The core, yes. One of the—for us—unexpected discoveries, with [Patric Hagmann](#), when we first looked at the atomic connectivity pattern of the human brain with diffusion imaging, was that there was a very highly- and densely-connected part of the brain that stood out amongst the others; and that was a set of regions in the [medial parietal cortex](#), which included structures like

⁶ Hans Berger is best known for inventing the EEG in 1924.

the [precuneus](#), the [posterior cingulate cortex](#), and things like that. We had never—in our work, in our reading—never really come across that very much.

And it only occurred to us as we were writing up our research that there was a lot of converging evidence that in that particular part of the brain there's something special going on. It's not only very highly-connected, as we found out, but also it has a very high level of resting metabolism; it is powerfully deactivated as a result of going into a state of unconsciousness. There are very interesting sociological and anatomical observations coming together. So, that part of the brain is really something that I think our studies contributed to identifying as an interesting, perhaps major hub region in the brain.

Dr. Campbell: The fact that it uses a great deal of metabolic energy implies that it must be awfully important in order for it to have been selected to...

Dr. Sporns: Yes. And if one wants to engage in metaphor here for a moment, you would imagine that if this region really is a major hub in the brain, that might account for the high degree of metabolic activation, because it simply has a lot of traffic passing through all the time, and it's participating in many, many conversations across the brain, tapping into information coming from many different sources. And that might account for that high level of metabolic energy. Whether that's really true or not is not known at this point. It's a speculation; but certainly one that might be worth looking into.

Dr. Campbell: Didn't you say something in the book about the activity of this area resembling what happens during cognition?

Dr. Sporns: This area is also very highly active in many cognitive tasks or mental states that involve self-reflection, thinking about the past and the future, retrieving memories. It's sort of part of a network that kicks into high gear when we're not engaged in anything cognitively demanding in the outside world. It is

part of a network that perhaps relates to ‘self’ processes. That’s something that came out of a number of social cognition and social psychology studies.

Dr. Campbell: Is the default core the only area that’s active when we are cognitively at rest?

Dr. Sporns: It’s a matter of degree. It is more highly activated when we’re cognitively at rest, but it is also active—although to a lesser degree—if we are engaged in a demanding task. It’s a question of balance of relative activation/deactivation in the brain. I think it’s fair to say no part of the brain is ever really completely shut off.

Dr. Campbell: OK.

So, I guess we could talk a little bit about a subject I know everyone is interested in, which is cognition. Obviously that’s a network phenomenon.

Dr. Sporns: You say ‘obviously.’ I’m glad to have persuaded you of that. I actually don’t know that that’s such a widely held belief right now. To me it is maybe not totally obvious, but it’s certainly an intriguing perspective. I think a lot of my colleagues in cognitive science still think of it more as a symbolic process that’s much more regionally specific than what’s implied by a network phenomenon. But I’m glad to hear you say it.

Dr. Campbell: Well, perhaps you could just talk about how the network perspective really does differ from other accounts.

Dr. Sporns: This is my own personal perspective, now, on this subject. I would like to approach cognition from a different viewpoint, really; not so much by taking 19th century categories of cognitive domains and applying them to the brain, but interrogating the brain and letting the brain answer back in terms of what are the domains of cognition that the brain supports. Is there perhaps an

anatomy of cognition? Are there specific networks in there that we can trace and delineate that will map onto different aspects, different domains of cognitive function, so we're getting a more bottom-up appreciation of where cognition comes from?

I have to be honest with you that there still are a lot of gaps to be filled here—coming from a network perspective like the one that I've been entertaining and writing about, going to and really understand the functioning of the human brain in terms of its cognitive abilities. I think there are still some gaps here that are not completely filled in; that require additional thought, additional work. But I think we're getting there; not least of all because of the efforts of people in neuroimaging, for example, who have been looking at connectivity at a much greater rate recently.

Dr. Campbell: One of the principles that you did emphasize in the book was the fact that segregation—for example, into modules, whether they be functional or anatomical—and integration are really opposing tendencies. The more modular things would be, the less they would necessarily be able to communicate.

Dr. Sporns: Yes; these are partly opposing—contradictory. If you want to have a totally modular brain, then you give up on integration. If you want perfect integration, then you lose your modules. So, it's a give and take; it's a compromise. And the way the brain has been, perhaps, evolving is to find an optimal trade-off between these two modes of functioning—between creating specialized domains and then also allowing them to interact.

I think what's also playing a role here is—and I come back to it; I mentioned it earlier—the three-dimensional embedding of the brain. The way it's really built in three-dimensional space rules out a lot of the ways in which it could actually be connected. It's actually in the book somewhere (and I'm forgetting the exact number now), but a randomly-connected brain, if we just took all your

connections and we wired them up at random, your brain would not fit in your skull any more. It would be much, much bigger; it would be like kilometers, or so, in diameter.

So, we can't even think of building a randomly-wired brain. It wouldn't be possible to do it, because we can't actually physically realize it. In my view, that's one of the things I've learned by writing the book. I wasn't fully aware of the importance of space and physical embedding for topology and for neural processing before I started writing this. And after I started reading more about it, I actually feel it's a topic I want to come back to sometime in the future.

Dr. Campbell: Yes. I'm glad you brought that up, because I think that was one thing you did talk about the first time that we talked, that got lost in the missing lost recording.

I want to quote something from your book, from Page 195, that I think is relevant to this part of the discussion. You said, "Modules of brain networks define communities of structurally or functionally related areas, but they do not represent or support discrete mental functions." Now, this is a statement that sort of goes against some of the more traditional cognitive science approaches; but one which I will say I agree with.

Dr. Sporns: Yes. I put that in there, actually, in part because a couple of years ago I gave a talk; I don't want to say where that was, but in the audience was a very famous cognitive psychologist. I started talking about graphs and about modularity, and this person in the audience sort of jumped up and said, 'What is this talk about modularity? This is old-style thinking,' and all of that. And I think there was a misunderstanding, because this audience member thought I was talking about modularity—in the line of [Fodor](#),⁷ perhaps—modularity of

⁷ Jerry Fodor is an American philosopher and cognitive scientist best known for his arguments in favor of the modularity of the mind.

mind, where we have separate faculties that are very much cut off from each other, and are actually autonomous.

And that's not what we talk about here. These are modules that are much, much more... You could think of them as little communities of loosely-bound elements that are interacting with each other, but they're certainly free to interact amongst each other, as well. I really want to underscore that the use of the term, 'modularity,' which has a different history in graph theory, does not imply that we're talking about cognitive modules of the type that perhaps others have proposed decades ago.

Dr. Campbell: And as your work and the work of many other researchers is showing, the dynamic nature of these brain networks implies that any place you look at could be participating in more than one functional module.

Dr. Sporns: Yes. I think that's not only likely, but I think in part already coming out from the studies that people have conducted. When we think of these networks, they are really overlapping with each other. And the same region of the brain—some regions more than others, I should say—the same region of the brain can certainly participate in different aspects of processing stimuli, or executing motor tasks, or what have you.

There are some regions that are, I think, very highly engaged and very universally engaged. Those are probably regions that we might refer to as these hubs—highly central regions of the brain that are coordinating information transfer between more specialized modules and groupings of brain regions. And those hubs are probably very highly active, no matter what we do.

Dr. Campbell: Olaf, what's the most surprising thing you've learned from applying network theory to the brain?

Dr. Sporns: There are many things that one discovers as one moves along. I think it's been interesting to see the prominence of some of the regions in the human brain that we've now identified on the basis of network theory as being centrally connected—as being hubs—and also see how we have a lot of physiology, a lot of classical anatomy that supports the notion that there are transmodal or multimodal regions. I think it's nice to see that agreement between more classical approaches and these more recent computational mathematical approaches.

I think there are many surprising things still to come. I think when we're starting to map the human connectome, and start to get a more complete picture of how networks are laid out, how they differ across individuals, how these network architectures relate to genomic variables, and so forth, I think there are really many, many surprises still to come.

Dr. Campbell: Do you have any advice for students that might be interested in getting into this field?

Dr. Sporns: I would certainly encourage students to become interested in this. I have taught, this semester, a course here at IU for graduate students—it's been very well attended—based on the book. And I've learned a lot from the students, actually, about what they're doing in their respective labs with neural recording techniques, but also recording behavioral data.

And we've explored together how we can use network approaches to get a better handle on understanding these data, modeling them, explaining patterns in the data, and predicting future outcomes. I think there's a lot of work still to be done. It's an open area. I hope that more and more young scientists become interested in this interesting field, and will make many contributions to come.

Dr. Campbell: Yes. What I think your work illustrates is that neuroscience is becoming such a multidisciplinary endeavor that there's room for everybody. No matter what background they start out with, they have something to offer.

Dr. Sporns: I completely agree. And I also tend to think—and this is my own subjective view—that there's really nothing boring about the brain. If you want to pick a scientific subject that's really exciting right now, and where almost everything that we do and explore has very immediate real-world consequences for the brain—how we understand how it works in health, but also in disease—this is a really fabulous subject to really sink your teeth in. And in neuroscience we need more people from computer science, from physics, from mathematics to come in and to give us the tools that we need to make sense of what we're seeing.

Dr. Campbell: Absolutely.

Do you have any final thoughts you'd like to share with my listeners before we close?

Dr. Sporns: Well, I certainly appreciate having had the opportunity to talk with you. I hope very much that the book will be useful to people who read it; will give them an idea of what it is that we're doing in this area, and perhaps stimulate future work and additional ideas. I think it's an ongoing research effort—obviously. Even though the book has only just appeared, there are already things happening now that are going beyond what's in there. So, stay tuned for Volume Two, which I am hoping to get to work on pretty soon. And I'm hoping that the whole topic will remain as exciting as it is now.

Dr. Campbell: Are you willing to take emails from students?

Dr. Sporns: Absolutely.

Dr. Campbell: I actually was looking through my email today—you know how you always have unanswered ones—and I found a question that someone sent me back in February, that was surprisingly relevant to your work. So, I suggested to them that they get your book. It was actually a question about brain evolution, and whether modularity represented an optimum wiring.

Dr. Sporns: Well, that's a good question. There are people working exactly on that. That's actually a very good question, because there are many aspects of modularity that have impact on the way the brain is built, and development, but on also how developmental programs might have evolved. There is reason to believe that it's a particularly compact wiring strategy, so it's good for volume preservation; but also for neural processing it might be really good, because of the small world features it gives rise to.

So, there are many, many things coming together right there. I think it's actually a very good question. I certainly get questions all the time, not only from my students here, but also from around the world—people who use the Toolbox, people who are reading something—and I'm always very eager to get those questions; and if at all possible, I try to respond to all of them.

Dr. Campbell: Thank you. And I thank you again for coming on the podcast.

[music]

I want to thank Dr. Sporns for taking the time to talk with me. As you might have guessed from my comments during the interview, we actually had to record this interview twice. I guess that's one of the hazards of being a one-woman operation; and I really appreciate his graciousness.

While [*Networks of the Brain*](#) is not a book for the general reader, it does provide an excellent introduction to the field. It does not contain any equations, but it does contain many real-world examples and excellent graphics. I highly

recommend it to all neuroscience students, and to listeners with a background in math, engineering, or computer science; and to anyone who is interested in learning more.

If you would like to learn more about the idea of small worlds, which we mentioned several times during the show, I have included additional references in the show notes at brainsciencepodcast.com.

Now I'm going to make a few brief announcements before closing today's podcast with a review of the key ideas from today's episode. First, I want to encourage you to visit the website, brainsciencepodcast.com. Besides detailed show notes and episode transcripts, you will find everything you might want to know about my work.

There are links to things like our [Facebook Fan page](#), and information about how you can [support](#) the show. There is also a place where you can leave a public comment about the podcast. And I hope you will sign up for the email [newsletter](#), so that you can get the show notes automatically every month. Of course, there are also links for subscribing, if you aren't already subscribed. Remember, it is free.

Next I want to thank those of you who send me emails from time to time about bad links on the website. If you go to the website and you find a bad link, please let me know, because that helps me correct the link for the next person.

Next I want to thank those of you who came out for my live talk in London last month. If you want to hear the raw, unedited version of my talk, "Why Neuroscience Matters," it is available as part of [Episode 84](#) of the *Pod Delusion* podcast—the episode dated May 13, 2011. I will post a link to this in the show notes. And I intend to put an edited version in the [Books and Ideas](#) feed sometime in June.

If you run out of *Brain Science Podcasts*, don't forget to check out my other podcast, [Books and Ideas](#). And if you're looking for science podcasts, check out the site I started back in 2008, called sciencepodcasters.org. By the way, I am always looking for new science podcasts to add to this site.

Depending on when you are listening to today's show, you may have heard an ad for the *Brain Science Podcast* app during the break. This app is available for [iPhone](#), [Android](#), and [iPad](#). I wanted to mention it has recently been updated for the iPad, which is the perfect device for reading episode transcripts. Since it's a universal app, if you've already bought it for your iPhone you don't have to buy it again; it will now work on your iPad.

Last, but not least, I want to mention that I will be participating in this year's [Amazing Meeting](#) in Las Vegas, Nevada, in July. You can find links to this in the show notes. Last year I enjoyed meeting quite a few listeners at TAM, and I hope I will meet more this year. If you are planning to attend, please drop me an email if you'd like to get together. Even if you can't attend, check out the website, because I think they stream a lot of the event live.

Because today's episode was more technical than usual, I want to spend a few minutes summarizing the key ideas. As I mentioned earlier, [network theory](#) is the application of the mathematical tools from [graph theory](#). It is an increasingly important tool for neuroscience, because it helps us cope with the vast amounts of data that are being generated by modern measurement techniques. It also provides a tool for making sense of the fact that nervous systems are multiscale phenomena that can't be reduced to any single scale.

One key idea that we touched on several times was the so-called 'small-world architecture,' which actually applies to a large number of real-world phenomena, including the Internet. If you want to learn more about small worlds, be sure to check out the references in the show notes.

Historically there has been an ongoing debate between scientists who focus on localization of brain function and those who emphasize integration. Network approaches reveal that the brain is really, as Dr. Sporns said, some of both. At its core, network theory is a tool for exploring connections. For the brain, this has at least three different aspects. It means exploring anatomical connections, functional connections, and then the third one is usually called ‘causal,’ which is trying to make a connection between the functional networks and the anatomical networks.

Network theory has to make use of various computational tools in order to analyze data and generate models. And from these models, experiments can be done to test the models, and also to generate more data. One of the points Dr. Sporns made was that there is no final model of the brain. That probably can be said for any field of science.

Another topic that we touched on was the idea of [degeneracy](#), which is the fact that biological systems often have many solutions for producing the same outcome. And we talked about [Eve Marder’s](#) work. If you would like to learn more about her work, I recommend going back and listening to *Brain Science Podcast* [Episode 56](#).

Another important concept is the idea that the wiring diagram, alone, is not enough. For example, we have had the entire wiring diagram for the nervous system of *C. elegans*—which is only 302 neurons—for over 25 years, and we still don’t understand everything about how its nervous system works.

One of the discoveries that has come out of applying network theory to data from neuroscience is the realization of what Dr. Sporns calls in his book, the ‘default core,’ which is a central highly-connected region that is spontaneously active at rest, and also during what you might call ‘inner-directed’ thought. When we interact with the world, the effect on the nervous system is, as he described it,

more like ripples on a body of water. He pointed out that there's no part of the brain that is ever completely off.

So, the key idea here is that, unlike our old model of thinking of the brain as just sitting there quietly, waiting for something to happen, what we now realize is that the brain is highly active, spontaneously on its own, and then interaction with the world perturbs that system, but it doesn't cause it.

Another subject that came up relates to our previous conversations on the *Brain Science Podcast* about embodiment. Dr. Sporns talked about the relevance of the 3D structure of the brain. He pointed out that the limits of the 3D structure of the brain rule out random connections as an organizational feature for the brain, because if every neuron was randomly connected in the brain, our brain would be way too big to fit into our skulls. So, the limits of 3D structure is just another reason why, as I've often said in the past, our brains are not computers.

The issue of modularity vs. integration is one that lends itself to network approaches. I want to re-read the quote that I mentioned during the interview, from Page 195 of *Networks in the Brain*, where he says, "Modules of brain networks define communities of structurally and functionally related areas, but they do not represent or support discrete mental faculties." Network methods reveal that the brain's modularity is different from earlier conceptions, because regions participate in multiple communities or modules, and these modules may be highly dynamic or rapidly changing.

So, I definitely agree with Dr. Sporns when he says, "There is nothing boring about the brain." And, as he pointed out, the field of network theory as it applies to neuroscience is a field that needs students from physics, engineering, math, and computer science. I emphasize this because I often get emails from people in these fields who want to get into neuroscience, and they don't seem to realize how much they have to offer. So, I want to emphasize that. Dr. Sporns said he is

eager to hear from those of you who are interested in the field, so I will put his email address into the show notes.

That's it for this month. I look forward to getting back on a monthly schedule on July 1st. Until then, I would love to hear from you. You can send me email at docartemis@gmail.com, or leave voicemail at 205-202-0663.

Thanks again for listening.

[music]

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